WSRC-MS-2003-00495

Experiences with non-traditional Bioassay Methods in a Plutonium Processing Line (U)

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Abstract

An incident in an SRS plutonium processing line (FB-Line) in 1999 highlighted the fact insoluble forms of plutonium exist at SRS that may not be readily monitored with the routine bioassay programs traditionally used at this site. To address this issue, a study was conducted in FB-Line with 21 participants for a year ending in July 2002. The purpose of the study was to examine the use of three non-traditional monitoring methods and, based on this experience, recommend a routine bioassay program that is capable of monitoring workers potentially exposed to insoluble plutonium. These non-traditional monitoring methods are personal air sampling (PAS), thermal ionization mass spectrometry (TIMS) of urine samples, and routine fecal bioassay. The main conclusions and recommendations of the study are:

• A routine TIMS urine bioassay program, which is called the enhanced bioassay program (EBP), is recommended for workers in SRS facilities that have a reasonable potential for exposure to insoluble forms of plutonium.

• Under certain conditions the EBP could result in onerous work restrictions. A contingency plan involving the use of PAS is recommended in this case. PAS is also recommended for workers who have had historic intakes of plutonium that interfere with the detection and interpretation of future intakes of insoluble plutonium.

• For the EBP to be successful it must be used only for those workers who have a reasonable potential for exposure to insoluble plutonium, and these workers must take all necessary precautions to avoid cross-contamination of the urine (and follow-up fecal) samples.

• Fecal bioassay is an important tool for follow-up to abnormal events, but routine fecal bioassay is not recommended.

• The PAS data clearly shows that workers are exposed to low levels of airborne plutonium, but the participants appear to be unlikely to exceed a committed effective dose equivalent of 100 mrem from these exposures.

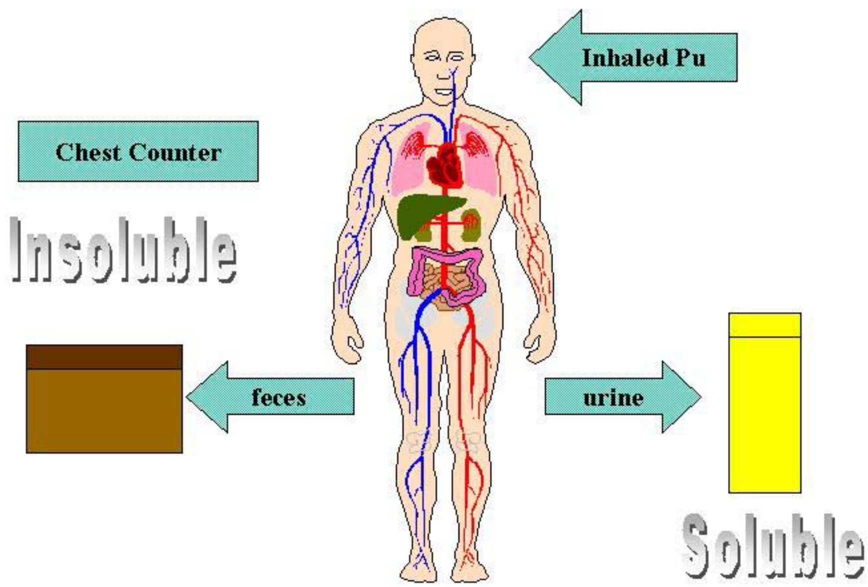
This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-96SR18500 with the U. S. Department of Energy.

Introduction

Plutonium that enters the body by inhalation can, among other things, be

- absorbed from the lungs into the bloodstream and eventually excreted in the urine,
- cleared from the lungs, swallowed, and eventually excreted in the feces,
- retained in the lungs and associated lymph nodes for an extended time.

In a simplistic sense, the urine bioassay gives an indication of the plutonium that has been absorbed from the lungs into the bloodstream ("soluble plutonium") whereas feces bioassay and chest counting give an indication of the plutonium that has not been absorbed into the bloodstream ("insoluble plutonium"). These concepts are illustrated in the diagram below.



Note that because chest counting measures the low-energy radiation emitted by radionuclides in the chest, pure weapons grade plutonium (i.e., no Am-241) is exceedingly difficult to detect and quantify.

The routine[a] internal dose monitoring programs for plutonium at SRS have traditionally used urine bioassay and chest counting exclusively. With few exceptions, feces bioassay has been used only in response to known events[b] and has not been used in routine programs. For decades there has been the concern that this traditional routine plutonium monitoring program would be incapable of detecting significant intakes of insoluble plutonium (for example, see Caldwell[1] and Skrable[2]), especially if the plutonium was freshly separated (i.e., no useful levels of Am-241).

In the early 1990's efforts were made to characterize insoluble plutonium in SRS facilities and to use a routine fecal monitoring program to determine if our routine bioassay program was missing

[a] In this context "routine bioassay" refers to bioassay performed at a prescribed time.
[b] This is referred to as "special bioassay."

significant intakes of insoluble plutonium. The final report on the fecal study concluded that workers in several locations appeared to be exposed to low levels of plutonium that could deliver a committed effective dose equivalent (CEDE) somewhere in the range of 50 to 500 mrem. This study had two major flaws that are relevant to current study:

- A worker was permitted to work in radiological buffer areas and then submit a fecal sample with no delay. As discussed later in this report, this can lead to positive fecal bioassay results that are difficult to interpret.
- The radiochemical method used to place the fecal sample into solution was not harsh enough to ensure complete dissolution of insoluble plutonium that could have been in the sample. This is a problem because the plutonium must be completely dissolved in order to be accurately detected and quantified.

These flaws, in combination with uncertainty concerning the intake pathway[a], made the study somewhat inconclusive beyond the fact that workers did not seem to be exposed to plutonium that would deliver doses in excess of the 5 rem annual effective dose equivalent (AEDE) limit in place at the time. The transition to a committed dose regulatory system that began the following year significantly diminished the importance of this conclusion[b].

9/1/99 FB-Line Incident

In September 1999, seven workers were exposed to airborne plutonium performing routine operations in a plutonium processing facility at the Savannah River Site[3]. The operation consisted of moving "bagless" transfer cans that contained plutonium metal buttons. These cans are welded stainless steel containers designed for the long-term storage of plutonium. As one of the cans was being handled a high volume air monitor (CAM) several meters away alarmed and indicated an exposure of approximately 17,000 DAC-hours. A follow-up investigation would eventually reveal that the weld on the can was defective and allowed air to enter the can. Exposed to the air, a substantial fraction of the plutonium metal converted to an oxide at a temperature of less than 70 degrees centigrade. All of the plutonium escaping the can is considered to be an oxide.

Chest counts, urine bioassay, and fecal bioassay were performed following the incident. These data indicated that the material inhaled by the workers was extremely insoluble, much more so than standard Type S material[c]. For this reason it is referred to as Type SS material (for "super S"). The filter from the air sampler was sent to Loveless Respiratory Research Institute for an in-vitro lung solubility analysis[4]. The results of this analysis support the conclusion that the material released during this incident is about an order of magnitude less soluble than standard Type S plutonium.

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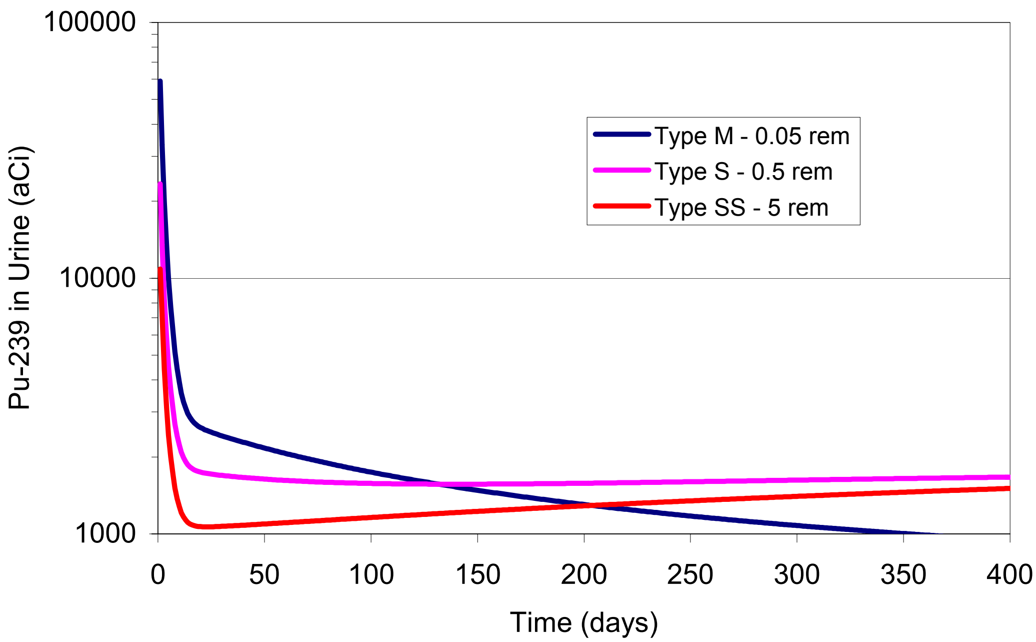
[a] Was the plutonium inhaled or ingested?

[b] A committed dose from an intake of plutonium can be roughly a factor of 50 larger than the annual dose from the same intake. So even though the committed dose limits were numerically equal to the annual dose limits, the actual dose limit went down by up to a factor of 50 with the switch from annual to committed dose.

[c] In the ICRP 66 classification of solubility in the lung, S refers to material that has a *slow* rate of solubilization and M refers to material with a *moderate* rate of solubilization.

Intakes of extremely insoluble forms of plutonium can be difficult to detect and assess using urine bioassay alone. For example, consider Figure 1 below, in which the urinary excretion rates of Pu-239 in the urine are plotted versus the time after acute inhalation intakes of Type M, S, and SS plutonium. The intakes of the different forms of plutonium were adjusted so that the excretion rates were similar. Specifically, the intake of Type M plutonium will deliver 0.05 rem CEDE, the intake of Type S will deliver 0.5 rem CEDE, and the intake of Type SS will deliver 5 rem CEDE. The urinary excretion rate is given in units of aCi[a] per day, where an aCi = 10^{-6} pCi. Note that the detection level for urine bioassay by methods currently in use at SRS (alpha spectrometry) is approximately 10,000 aCi.

Figure 1. Comparison of urinary excretion rate following intakes of plutonium.



There are two important implications of this plot. First, the traditional alpha-spec urine bioassay program used at SRS cannot be used to reliably detect significant intakes of insoluble plutonium[b]. Second, urine samples alone may not be able to readily distinguish an insignificant intake of Type M material from a significant intake of Type SS material. In the 1999 FB-Line incident we were fortunate that the material had a significant Am-241 tracer that permitted us to use chest counting to quantify the intake. If the plutonium had been recently processed (i.e., there was no Am-241 tracer) the cases would have been much more difficult to evaluate because we would have had to rely primarily on fecal excretion data to estimate the intakes and doses. Without fecal bioassay, significant intakes of this freshly separated material would be essentially undetectable.

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[a] An aCi is an exceedingly small amount of radioactive material. To illustrate this fact, consider that 1 aCi = 1.2 dpy (disintegrations per year).

[b] The chest counting program is the last line of defense in this case, but for it to be effective there must be a relatively high Am to Pu ratio, and we must have a good idea of the value of this ratio and the time of intake.

This incident raises some troublesome issues for the bioassay programs at SRS because this material was not created by some exotic process like high firing in a furnace. This implies that very insoluble plutonium may be encountered in workplaces where it was not expected. To address this issue we decided to run a pilot monitoring program in FB-Line that employed three non-traditional bioassay techniques.

The FB-Line Pilot Program

There are three non-traditional methods that have the ability to meet the requirements of 10CFR835.402(d) and are considered candidates for routine internal dose monitoring of insoluble plutonium at SRS. Other methods exist that might also show promise, but only these three are currently in routine use at other facilities in the DOE Complex:

- Personal lapel air samplers (PAS), which consist of a small air pump that is worn on a belt and a filter sample head that is positioned near the lapel area. The advantage of the PAS is that it samples air that is much more representative of what the person breathes than the typical area air monitor.
- Routine fecal bioassay measures the fraction of inhaled plutonium that is not dissolved in the blood but rather is cleared from the lungs into the GI tract. This is a very useful method for detecting intakes of insoluble plutonium and is currently used at SRS only in the special bioassay program.
- Thermal ionization mass spectrometry (TIMS) of urine is an analytical method that has a detection level for weapons grade plutonium that is 30-60 times lower than that obtainable with alpha spectrometry that is currently used for urine bioassay. The lower detection level permits us to use urine bioassay to detect intakes of the more insoluble plutonium compounds.

In the FB-Line pilot program, these non-traditional methods were used in addition to the current routine and special bioassay programs[a] to monitor 21 workers[b]. The primary objective of the pilot program was to gain experience with the actual use of non-traditional bioassay methods so as to identify the most cost-effective options for their general use in FB-Line and on site. Secondary objectives of the pilot included

- Compare personnel exposures measured with PAS[c] with exposures measured with area air samplers to determine how well area air samplers predict the exposure to workers (are area air samplers representative?),
- Compare the results of PAS[d] with special urine and fecal bioassay, and
- Perform a follow-up to the previous fecal study.

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[a] The routine program consists of a one-liter urine sample analyzed by alpha spectrometry and a 30-minute chest count, both with an annual frequency. The special bioassay program typically consists of two 24-hour urine samples, a fecal sample, and a chest count.

[b] The workers were selected by FB-Line management and were comprised of operators (OPS), radiological control inspectors (RPD), and security officers (WSI). Maintenance workers were not selected because they work in other facilities in addition to FB-Line.

[c] This objective may be met only for those workers wearing PAS 100% of the time.

[d] This objective may be met only for those workers wearing a PAS during an exposure (incident).

Description of PAS Monitoring
The PAS itself consisted of a SKC Model 224-44XR air pump with an SKC 37-mm closed face filter cartridge loaded with a Whatman Grade GF/A glass fiber filter. The nominal airflow for the pump was 4 liters per minute. Workers were instructed to wear a PAS whenever they entered the FB-Line radiological buffer area (RBA) and to change filters when they put a full-face respirator on or took it off. All filters were counted for 10 minutes on one of four different Tennelec Series-5 gas-flow proportional counters after a minimum 7-day decay period.

With the implicit conversion of units, the amount of plutonium inhaled when a worker is exposed to 1 DAC for 1 hour is

$$\left(2 \times 10^{-12}\ \frac{\mu Ci}{mL}\right)(1\,hr)\left(20\frac{liters}{\min}\right) = 2.4\,pCi$$

where

$2x10^{-12}$ μCi/mL = the DAC for soluble Pu-239 given in Appendix A of 10CFR835
20 liter/min = breathing rate of Reference Man

The exposure in DAC-hours is calculated from the filter paper as shown below:

$$DAC - hour = \left[\frac{X\ pCi}{2.4\,pCi}\right]\left[\frac{20000\,mL/\min}{F\ mL/\min}\right]$$

where

X = the alpha activity on the lapel filter
F = the mean flow rate of the PAS pump

For example, if the alpha activity on the filter is 0.7 pCi and the mean flow rate is 3982 mL/min, the exposure in DAC-hours is

$$DAC - hour = \left[\frac{0.7\,pCi}{2.4\,pCi}\right]\left[\frac{20000\,mL/\min}{3982\,mL/\min}\right] = 1.46\,DACHr$$

The length of time the PAS was worn is not required in this approach to calculating exposure. The only requirement is that the PAS and worker are both exposed to the same atmosphere for the same length of time. The detection level for PAS is taken to be 1 DAC-hour.

Description of TIMS Urine Bioassay
Traditionally, urine bioassay for plutonium has been performed at SRS by alpha spectrometry. This method infers the number of plutonium atoms present in a sample by the alpha radiation given off by the small fraction of atoms that decay during the time period for which they are observed. Mass spectrometry on the other hand attempts to count the atoms directly, providing a lower detection level for long-lives isotopes of plutonium like Pu-239. The alpha radiation

emitted by Pu-239 and Pu-240 have essentially the same energy, which means that any analysis for Pu-239 is more properly called an analysis for Pu-239/240. On the other hand, because TIMS differentiates isotopes by mass, it can measure Pu-239 and Pu-240 individually. The practical implication of this is that Pu-239 measured by alpha spectrometry is actually Pu-239/240 whereas Pu-239 measured by TIMS is actually Pu-239. Isotopes of plutonium with short half-lives (like Pu-241 and Pu-238) and isotopes with common isobars (U-238 is an isobar of Pu-238) are not as readily measured with TIMS as are Pu-239 and Pu-240.

TIMS analysis of the SRS urine samples was performed by the Chemistry Division of the Los Alamos National Laboratory (LANL) using the same procedures used for routine LANL urine samples. The urine samples are first processed for alpha spectrometry by radiochemically separating the plutonium and electrodepositing it on a stainless steel planchet. The results of the alpha spectrometry are not presented in this report but may be found in the original analytical reports issued by LANL.

All chemistry done to support the preparation of the TIMS samples is conducted in a clean room environment. The stainless steel planchet from alpha-spectroscopy analysis is washed with a hydrofluoric/nitric acid solution to remove the plutonium. The plutonium solution is passed through an anion exchange column and the plutonium is eluted from the column by addition of a hydrochloric/hydroiodic acid solution. The sample is evaporated to dryness and re-dissolved in a hydrochloric acid/peroxide solution. The sample is loaded on a second anion exchange column and plutonium is eluted from the anion exchange column with hydrobromic acid, into a pre-cleaned quartz test tube.

The solution is electroplated onto a rhenium filament, which is inserted into the ion source of the mass spectrometer. A current is passed through the filament, which causes the plutonium isotopes in the sample to ionize. The ions are accelerated through a magnetic field, resulting in separation of the ions by mass, with heavier ions having more momentum. An electron multiplier allows the number of ions of each isotope to be counted. The amount of Pu-239 in the original sample is calculated by comparing the number of those ions to those resulting from a known amount of Pu-242 spike. The Pu-242 tracer was added to the sample prior to electroplating. The detection level for TIMS analysis is taken to be 300 aCi (0.0003 pCi) of Pu-239 per sample in this report.

Description of Fecal Bioassay

The participants in the study were instructed to submit fecal samples after at least a 2-day absence from the RBA. If feasible, they were encouraged to collect samples after longer absences (like a long 7-day weekend or a vacation). These protocols were adopted to minimize the risks of false positives caused by cross contamination or ingestion intakes.

The analysis of fecal samples was performed at SRS. This process begins with the fecal samples being placed in a plastic carton and dried to a constant weight. The samples are then ignited in a porcelain crucible using a gas burner, and then ashed in a muffle furnace for 8-16 hours at 500° F to produce less than 5 grams of ash. The Environmental Monitoring Section then counts the sample for one hour on a germanium detector. Typical MDAs are on the order of 7 pCi for Am-241, 300 pCi for Pu-238, and 600 pCi for weapons grade plutonium. If the sample contains detectable activity, further radiochemical analysis is not attempted and the sample is analyzed by low-energy gamma spectrometry.

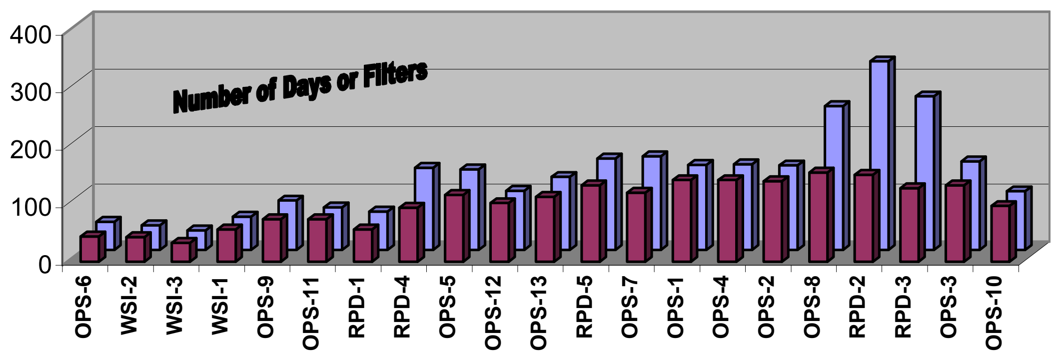
If the sample does not contain detectable activity, sample dissolution is performed and the sample is analyzed by alpha spectrometry. Any radioactive tracers needed for the analysis are slowly pipetted on to the sample ashes at this point. The ashed sample is dissolved by first using nitric acid and hydrogen peroxide followed by dissolution in hydrochloric-hydrofluoric acids then hydrofluoric-boric acids. Both the hydrochloric-hydrofluoric and hydrofluoric-boric fractions are added to Diphonex resin, which retains the actinides present in the sample and other heavy metals including strontium. Microwave dissolution is then performed to destroy the resin with the actinides then dissolved in nitric acid and chemically separated like urine samples. Intercomparison tests with the USDOE Radiological and Environmental Sciences Laboratory (who employ fusion techniques) involving highly insoluble plutonium oxide samples have shown that this method is harsh enough to ensure complete dissolution of the plutonium in the sample. The nominal detection level for fecal bioassay is on the order of 0.05 pCi.

PAS Results

An overview of the PAS results will be presented in this section. A summary of PAS results for each of the 21 participants is presented in Appendix A of this report. An important parameter that influences conclusions drawn from the PAS data is the usage of PAS during the study. In Figure 2, the front histograms are the number of days during which workers wore a PAS, which ranged from a low of 33 days (shifts) for WSI-3 to a high of 155 days (shifts) for OPS-8.

A low number of days worked might indicate that a person did not wear a PAS on every RBA entry and/or the person did not work in FB-Line very often. Let us first address the question of how many days was each participant expected to work in the FB-Line RBA? The operators and inspectors in FB-Line generally work a 12-hour shift. This means that, taking all things[a] into consideration, it is reasonable for a full-time FB-Line operator or inspector to work in the FB-Line RBA somewhere in the range of 115 to 150 days per year (see Appendix A).

Figure 2. Usage of PAS.



The security officers are assigned to posts both inside and outside the facility, so they are not expected to work as many days in FB-Line per year[b] as operators or inspectors. Although a few of the participants in the study did not seem to work in the FB-Line RBA as much as might be expected, we will consider the observed work rates to be typical for such a population. Concerning the use of PAS on each entry, although the participants in the study were asked to wear a PAS whenever they entered the FB-Line RBA, compliance with this request was not directly confirmed. Nevertheless, for the purposes of this report, we will assume that the workers indeed wore a PAS on every RBA entry.

The number of PAS filters used during the study is presented in the back histograms of Figure 2. Participants like RPD-2 who frequently wore full-face respirators or worked under multiple radiological work permits (RWPs) during the day tended to use multiple filters (328 filters in 151 days). Participants in the study were selected from those workers expected to be less likely to wear multiple respirators because of the inherent problems with changing filters frequently. Evidently, some had no choice because of job assignments and schedules. Thus, these workers had to frequently change respirators and thus use multiple PAS filters per shift.

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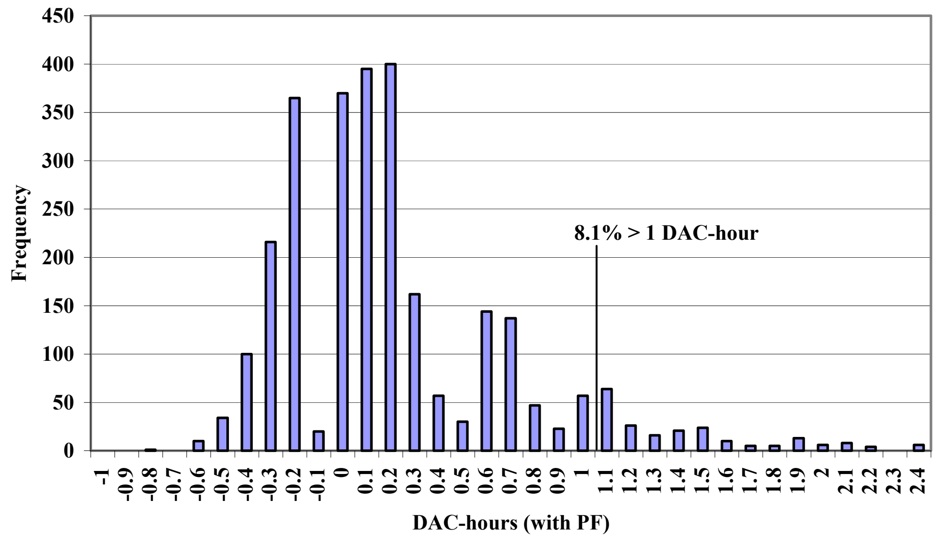
[a] Holidays, vacation, training, other work assignments, etc.

[b] Also note that security personnel do not wear respiratory protection under normal conditions.

A summary of the exposure measured with all 2794 PAS filters used during the study is presented in Figure 3. The decision level (DL) for a single PAS filter is taken to be 1 DAC-hour. This means that an exposure of greater than 1 DAC-hour is considered to be statistically significant, i.e., it indicates a "real" exposure to plutonium. Approximately 8% of the filters collected during the study indicated a measurable exposure to plutonium. The highest single exposure (which is not shown in Figure 3) was 120 DAC-hours to OPS-7, who was wearing a full-face respirator at the time.

Figure 3. Summary of all PAS results.



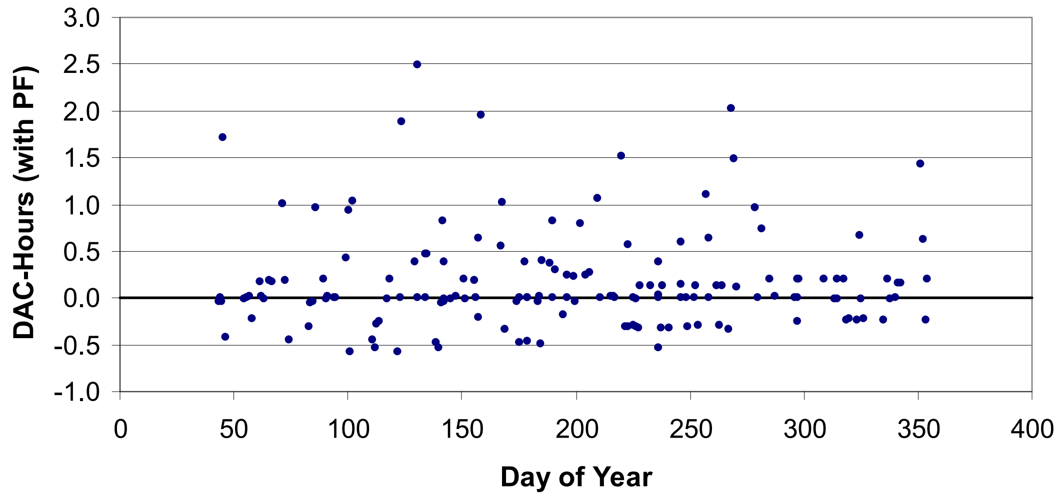
The PAS results for inspector RPD-5 are presented in Figure 4. The x-axis is the number of days elapsed from 7/1/01, which is the start of study. The y-axis is the exposure in DAC-hours. If a full-face respirator was worn a protection factor (PF) of 50 was applied to the exposure[a]. No PF is applied for plastic suit or fresh-air hood use because the PAS is worn with the person inside the suit or hood. Negative (numerically less than zero) exposures occur when the background counts are greater then the gross counts from the filter. Plots like Figure 4 are presented in Appendix A for all participants of the study.

The annual cumulative exposure may be calculated in a number of different ways:

1. Simply sum the exposure measured with each filter (31.8 DAC-hours for RPD-5).
2. Apply a PF of 50 to exposures received while wearing a full-face respirator and then sum the exposures (26.4 DAC-hours for RPD-5).
3. Apply the DL to the exposures (i.e., ignore any exposures less then 1 DAC-hour), apply the PF, and then sum the exposures (19.8 DAC-hours for RPD-5).

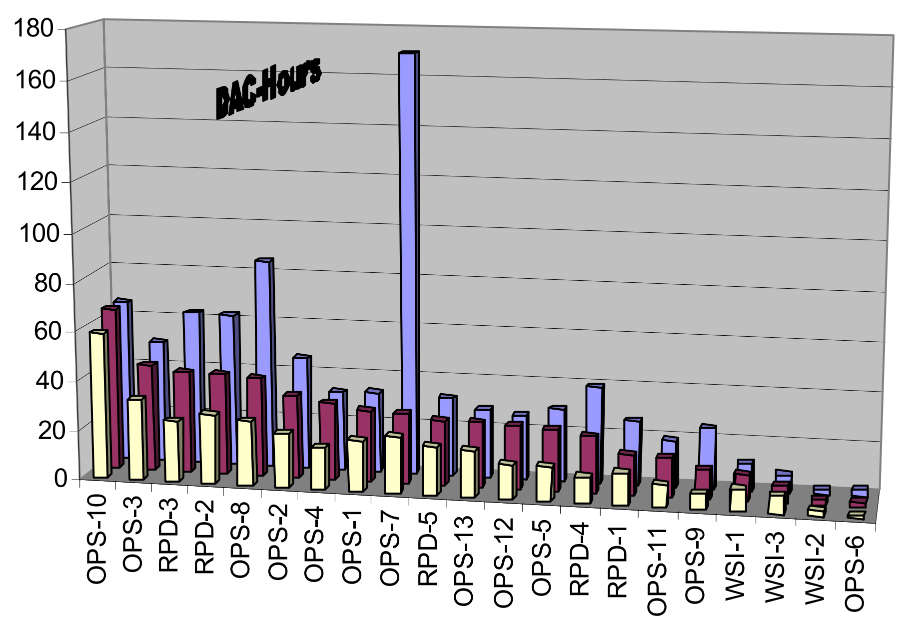
Figure 4. PAS results for RPD-5.

[a] Which reduces the exposure by a factor of 50.



The second method is considered the most appropriate and will be used in this report to calculate cumulative exposures. However, the cumulative exposures calculated by all three methods for the participants are shown in Figure 5, which clearly shows that OPS-7 was the worker who received the 120 DAC-hour exposure while wearing a full-face respirator.

Figure 5. Cumulative exposures for study participants. Cumulative exposures calculated by Method 3 are the front histograms, Method 2 the middle histograms, and Method 1 the back histograms.

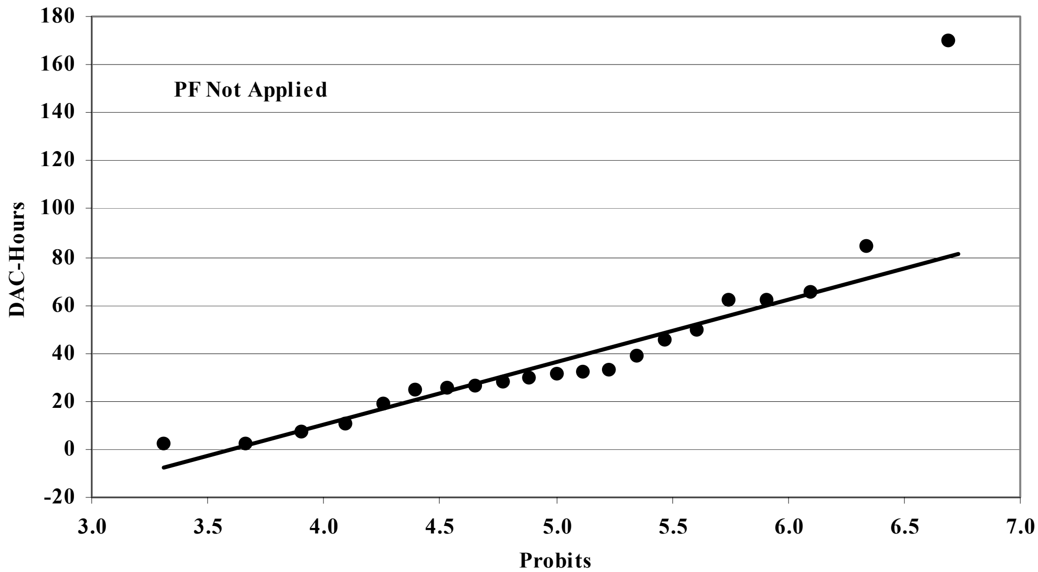


In Figures 6 through 8 the annual cumulative exposures are presented on probit plots[5]. Probit plots are a convenient way of testing if the data are normally distributed: if the data form a straight line on a probit plot then one may assume that they are measurements taken from a population of normally distributed random variables. It is also useful to know that

- A probit of 5 indicates the median of the data, i.e., 50% of the observed data are less than the measurement that has a probit value of 5.
- A probit of 6.645 is the 95th percentile of the data, i.e., 95% of the observed data are less than the measurement that has a probit value of 6.645.

The straight lines in Figures 6 through 8 are the lines of best fit to the data excluding the last datum[a]. Because the data seem to be normally distributed, we can calculate the probability of observing an annual cumulative exposure of more than 100 DAC-hours[b] from the line of best fit.

Figure 6. A probit plot of the annual cumulative exposures calculated by Method 1.



Even for Method 1, which gives the highest cumulative exposures, the probability is less than 1%. Assuming that the participants indeed wore their PAS whenever they entered the FB-Line RBA, this data seems to support our contention that workers in FB-Line are unlikely to exceed 100 mrem in a year. This conclusion takes on greater significance when one considers that there was a considerable amount of radiological work being performed in FB-Line during the period of the study. The major uncertainty in this conclusion revolves around the question of did we select the right population of workers to monitor? In other words, when we try to determine the probability of exceeding 100 mrem in a year should we look at a cross-section of all FB-Line workers or include only those personnel who work a minimum number of shifts in the RBA per year (115 for example)? We are not aware of any guidance on this issue, so the question will go unanswered for now.

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[a] It is common for the last few data points at the extremes of the plot to significantly deviate from the line, so the last datum was ignored for the purposes of fitting a line to the data.

[b] Where 100 DAC-hours = 100 mrem (see Appendix B).

Figure 7. A probit plot of the annual cumulative exposures calculated by Method 2.

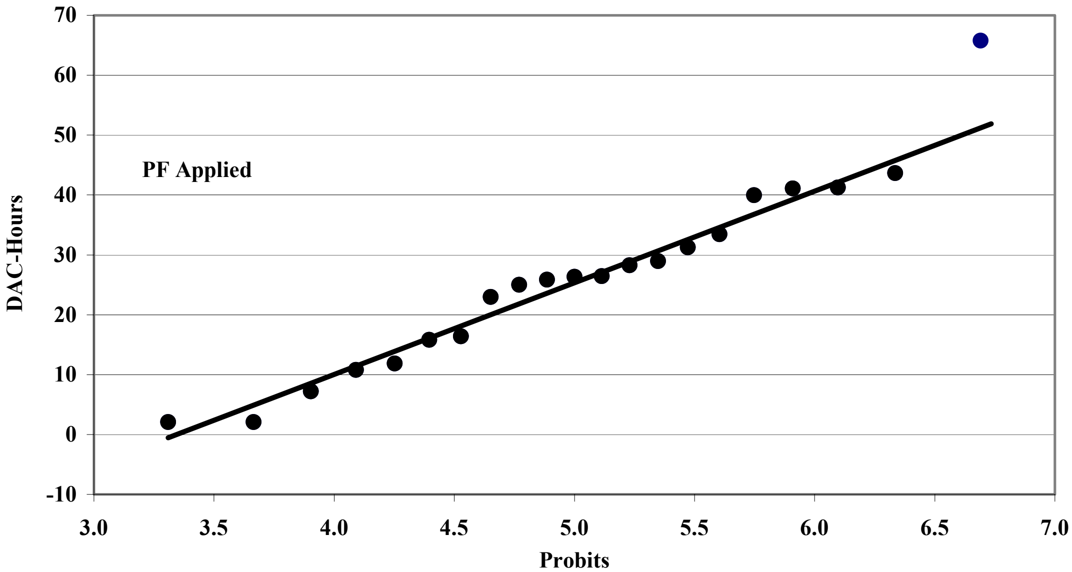
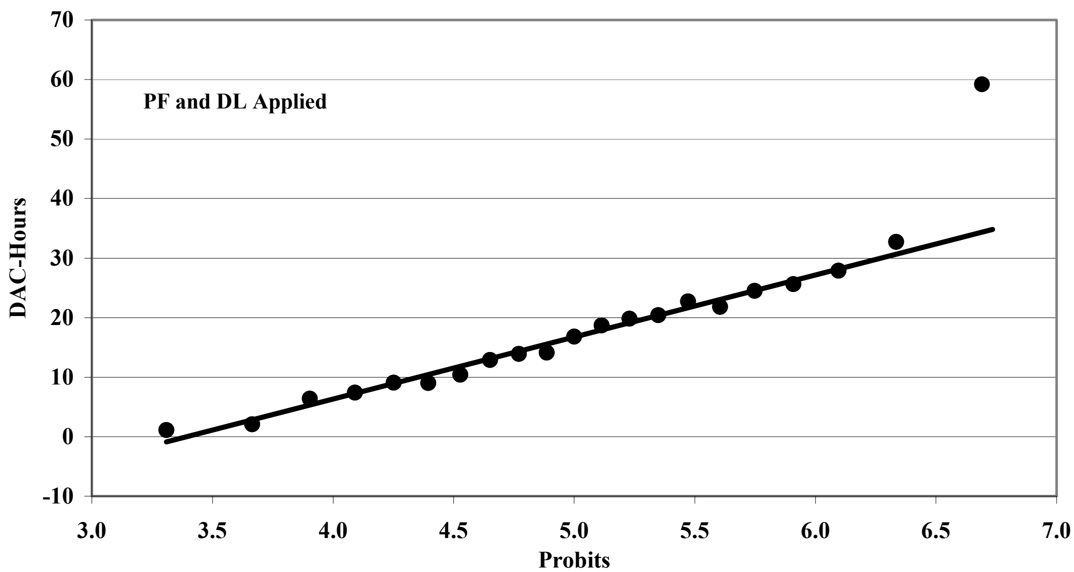


Figure 8. A probit plot of the annual cumulative exposures calculated by Method 3.

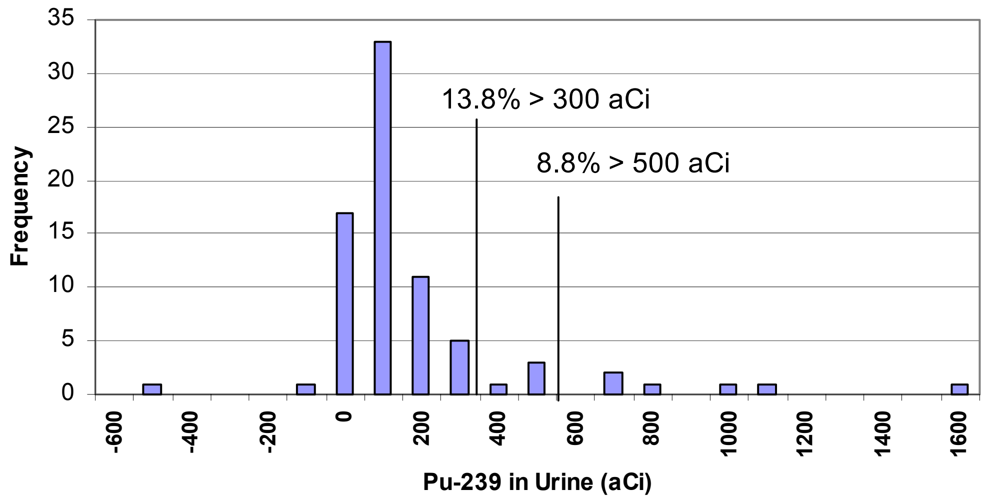


TIMS Urine and Fecal Bioassay Data

The results of the TIMS are shown in Figure 9. Of the 84 urine samples sent to LANL, 5 were reported as LIA, or "lost in analysis. These samples did not pass the laboratory QC criteria and no results were reported. Approximately 14% of the samples were above the detection level of 300 aCi. An action level of 500 aCi, which corresponds to a CEDE of 2 rem for Type SS weapons grade plutonium, was established. Approximately 9% of the samples exceeded this action level[a]. The results of the TIMS bioassay are discussed further in the case narratives.

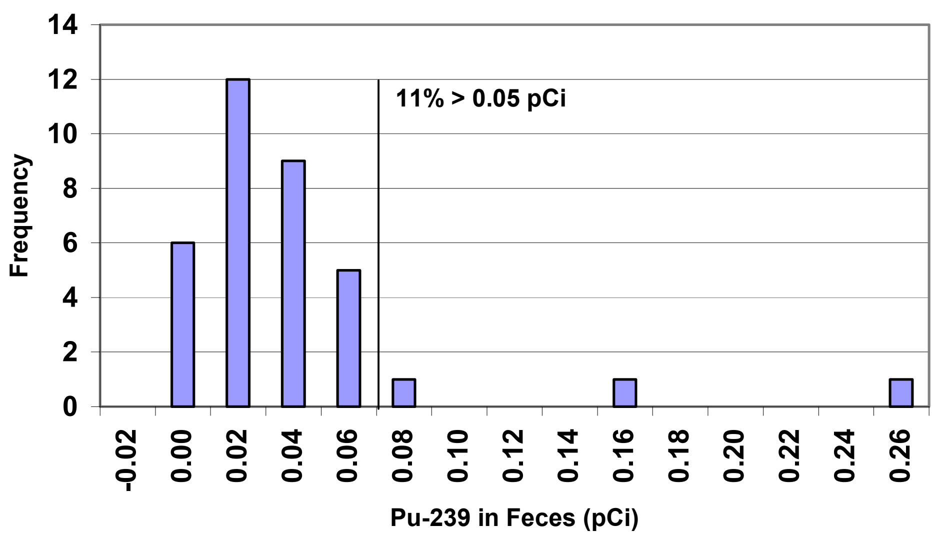
[a] Just because a result is in excess of 500 aCi does not mean that the person received over 2 rem. As discussed later, the action level was established to identify a point at which a particular type of bioassay program would be implemented.

Figure 9. Results of TIMS urine bioassay.



As one can see in Figure 10, 11% of the fecal samples collected were above the detection level for Pu-239[a].

Figure 10. Results of Pu-239 fecal bioassay.



In comparison, approximately 63% of the fecal samples collected in FB-Line for the 1992 Fecal Study were above the detection level for Pu-239, which was also 0.05 pCi. The six-fold reduction in the number of positive samples observed between the 1992 and 2002 studies could be attributed to a number of differences between the two studies, but we must consider the RBA access restrictions to be a major factor.

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[a] Four of the routine fecal samples collected were positive for Am-241.

Selected Case Narratives and Further Discussion

OPS-12
On 12/7/01, operator OPS-12 and two other workers entered an airlock, which is a non-ARA[a], from a room that is an ARA. They were not wearing respiratory protection in the airlock but OPS-12 was wearing a PAS. The PAS filter was not counted at the end of the day[b]. Three days after the event the filter for the air sampler in the airlock was counted and indicated an exposure of 14.2 DAC-hours. As part of the investigation into potential exposure an attempt was made to count the PAS filter, but it could not be located. The PAS filter was apparently lost and was never counted. The individuals were placed on a special bioassay program consisting of a single 24-hour urine sample and a sample slated for TIMS analysis was collected from OPS-12 on 12/19/01. The special urine sample was less than the DL for $^{239/240}$Pu [c] and the TIMS was less than the DL for ^{239}Pu. No intake was assigned to this individual.

The lost PAS filter is an isolated event, but it illustrates a significant weakness (one which is rarely discussed) of using PAS to monitor workers. Specifically, PAS must be performed <u>while</u> the exposure to the worker is occurring. Bioassay is much more forgiving in this respect because it can be performed as many times as desired after an exposure has occurred. Thus, the real trick to using PAS is to accurately anticipate who will be exposed and ensure that they are wearing a functional PAS when they are exposed. This can be difficult to do in practice.

OPS-6
This case clearly illustrates why TIMS urine bioassay is not a panacea for the problem of highly insoluble plutonium. Urine and feces bioassay data for operator OPS-6 are presented in Table 1 below. Results above the decision level are in bold type.

Table 1. Bioassay data for OPS-6. See Appendix A for a discussion of terminology.

Date	Nuclide	Sample Type	Result (pCi)	DL (pCi)	2σ error (pCi)
4/17/2001	Pu239	AS urine	0.006144	0.012883	0.010865
8/11/2001	**Pu239**	**feces**	**0.021923**	**0.019455**	**0.021027**
4/25/2002	Pu239	AS urine	0.005856	0.009009	0.008559
8/10/2001	Pu239	MS urine	LIA		
11/25/2001	**Pu239**	**MS urine**	**0.001580**	**0.000300**	**0.000101**
2/21/2002	**Pu239**	**MS urine**	**0.000674**	**0.000300**	**0.000319**
6/22/2002	**Pu239**	**MS urine**	**0.000920**	**0.000300**	**0.000051**

[a] It was not an airborne radioactivity area (ARA).
[b] Few filters were counted on the day they were used until the AB-14 counter, which is capable of discriminating against radon/thoron daughters, became operational in March 2002.
[c] The urine sample was reported to contain extremely low levels of Am-241. Considering the TIMS result, the ^{241}Am result is not considered to indicate that an intake of weapons grade plutonium had occurred.

This individual wore a PAS on 44 days and had a cumulative exposure of only 2.8 DAC-hours[a], not applying a protection factor for any respiratory protection used. He has not ever been assigned an intake and has not been placed on any special bioassay programs in the last ten years. Nevertheless, his fecal and TIMS urine samples were consistently above the detection level for ^{239}Pu (the 8/10/01 urine sample was lost in process at LANL). The intake responsible for the observed bioassay data could have occurred during the study period or at some time in the past -- the true time and nature of the intake is unknown. Nevertheless, we can apply three different standard models to evaluate the data. Assumptions common to all three evaluations are

- The intake was an acute inhalation on 7/1/01, which is the start of the study.
- The inhaled material was weapons grade plutonium.

Assuming an acute inhalation intake of Type M (soluble) weapons grade plutonium, the intake is estimated to be 1.75 nCi. When we refer to the activity of *weapons grade plutonium* in these examples note that approximately 81% of this activity (1.42 nCi) is ^{241}Pu, which decays to ^{241}Am but does not itself emit any alpha radiation. The remaining 19% of the activity (0.33 nCi) is ^{238}Pu, ^{239}Pu, and ^{240}Pu and ^{241}Am, which do emit alpha radiation. These isotopes of plutonium and americium are collectively referred to as αPu. The αPu is what is measured on the PAS filter when it is analyzed by the counting lab on a gas-flow proportional counter. The ^{241}Pu, which does not emit alpha radiation, is not quantified on the gas-flow proportional counter[b].

If we work the problem in the forward direction perhaps things may be clearer. Assume that a PAS filter was alpha counted on a gas-flow proportional counter and was found to have collected 66 pCi of activity, which is αPu. Given that the PAS pump ran at 4 liters/min and the person breathed at 20 liters/min, the person is assumed to have inhaled

$$\left(\frac{20}{4}\right)(66\,pCi) = 330\,pCi$$

of αPu. Thus, assuming 1 DAC-hour of αPu is equivalent to an intake of 2.4 pCi (see Appendix B), the 330 pCi intake of αPu is equivalent to an exposure of

$$\left(\frac{330}{2.4}\right)(1\,DAC-hour) = 138\,DAC-hours\ .$$

Remember that this exposure does not include the ^{241}Pu. Of the 330 pCi intake of αPu, 218 pCi is ^{239}Pu. At 235 days following the intake, 4.753E-6 of the 218 pCi (1.036E-3 pCi or 1036 aCi) is expected to be in a 24-hour urine sample. Finally, if we took the 1036 aCi of ^{239}Pu in the urine on day 235 and worked backwards to get the intake of *weapons grade plutonium*, we would obtain the 1.75 nCi estimate.

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[a] This exposure is not considered to be significantly different than background.

[b] The ^{241}Pu emits primarily a low-energy beta particle that has a low counting efficiency.

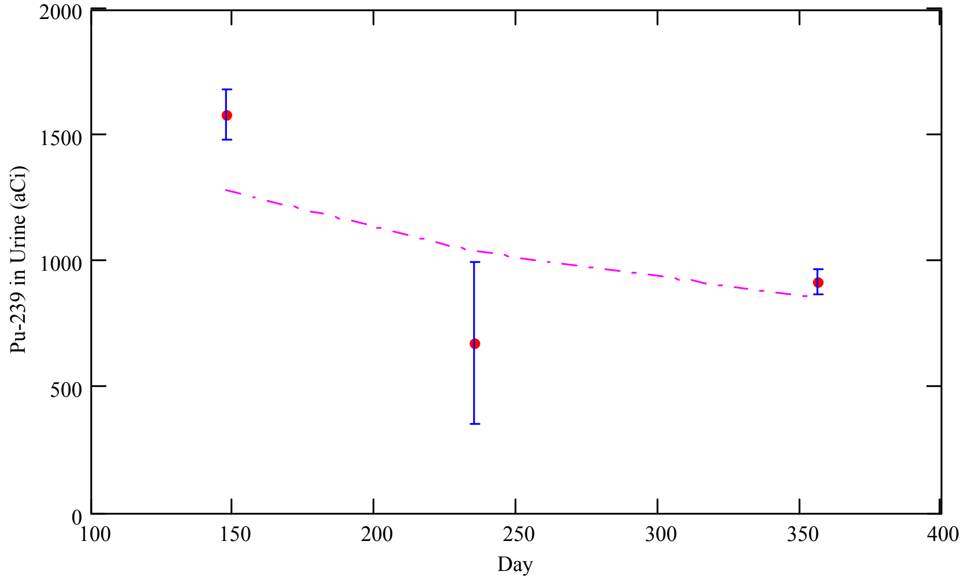
In this report the ICRP 60/66/67 models are used to calculate intake from bioassay data because these models are generally regarded to be the best available for this purpose. The dose calculated using the ICRP 60/66/67 models is the *committed effective dose* (CED), which is different than the *committed effective dose equivalent* (CEDE) calculated with the ICRP 26/30 models. For example, the CED (not CEDE) calculated from a 1.75 nCi intake of weapons grade plutonium (not αPu) is 43 mrem. Given a 1.75 nCi intake, the CEDE *could* have been calculated. However, this CEDE would be of dubious value because had the ICRP 26/30 models been used to evaluate the bioassay data the intake would not have been 1.75 nCi.

On the other hand, because the intake calculated from a given exposure is essentially the same for both models, we can calculate both the CED and the CEDE from PAS results with a clear conscience. A popular rule-of-thumb is that one receives 2.5 mrem per DAC-hour of exposure. In general, 1 DAC-hour, *as reported by the counting lab*, of soluble weapons grade plutonium will result in a CEDE of approximately 1.0 mrem and a CED of 0.3 mrem. Thus, this 138 DAC-hour exposure is expected to deliver a CEDE of roughly 138 mrem and a CED of 41 mrem. This CED is somewhat lower than the 43 mrem calculated from bioassay data primarily because it does not include the contribution from the ^{241}Pu, which is not accounted for by PAS.

This exercise illustrates that comparing PAS and bioassay can get quite confusing because PAS and bioassay measure different things. Thus, in this report PAS will be compared to bioassay primarily by comparing the exposure measured by PAS (*as reported by the counting lab*) with the exposure that is consistent with the intake calculated with ICRP 66/67 models applied to bioassay data. In any discussion of doses the reader must take careful note of which intake (weapons grade or αPu) and which dose (CED or CEDE) is being referred to at any given point.

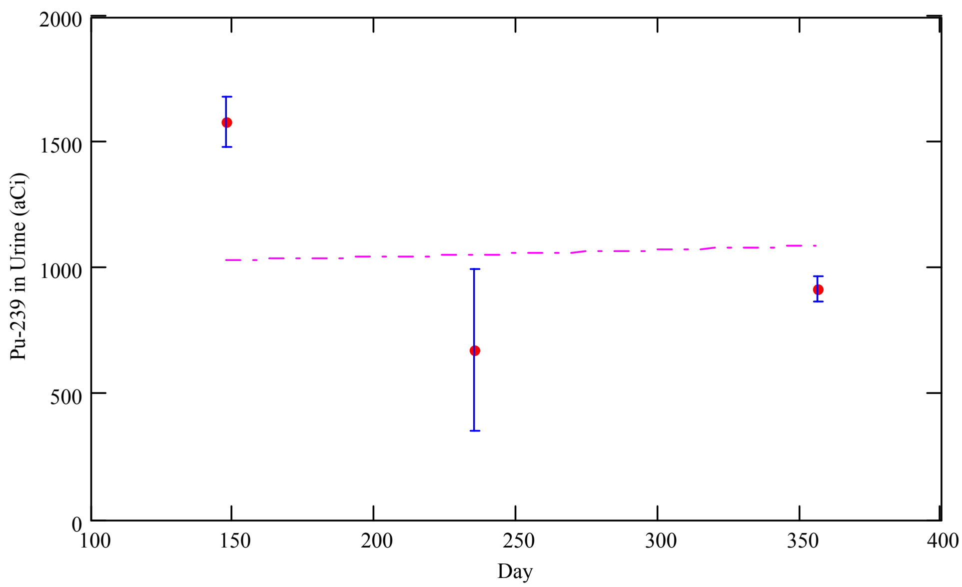
The plot of observed and predicted urinary excretion is presented in Figure 11 below. The shape of the predicted urinary excretion curve is fixed by the biokinetic model selected. This means that in a least-squares fit of the line to the data, the line can only be moved up (larger intake) or down (smaller intake) to minimize the sum of squares. The 2σ uncertainty shown for each datum reflects the variance in the analytical measurement and does not include biological variance. The $^{239/240}$Pu excretion in feces predicted for the 8/11/01 sample is 0.057 pCi compared to the 0.022 pCi observed, which is reasonably good agreement.

Figure 11. Predicted and observed urinary excretion assuming an inhalation intake of 1.75 nCi of Type M weapons grade plutonium.



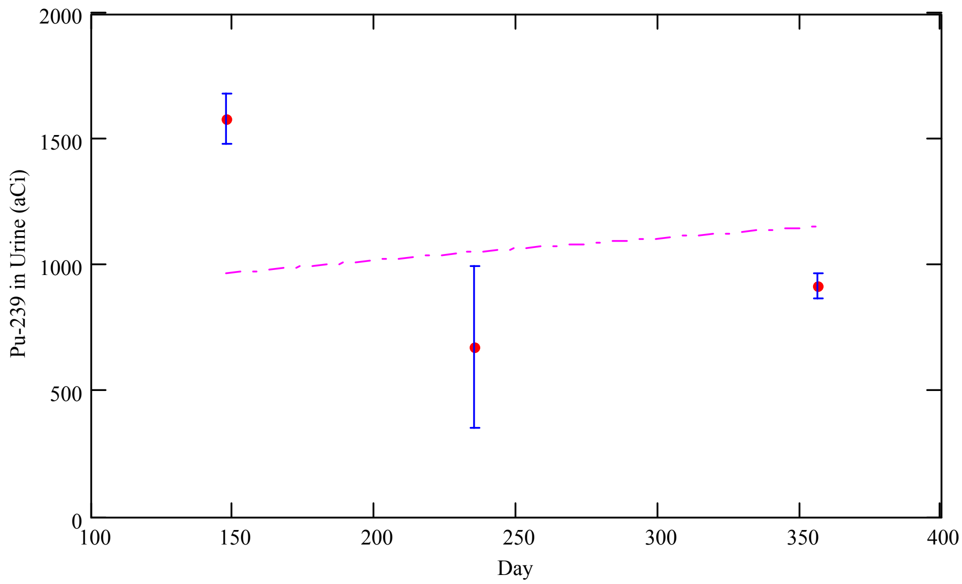
Assuming an acute inhalation intake of Type S (insoluble) weapons grade plutonium on 7/1/01, the intake is estimated to be 52.8 nCi. This intake, which is equivalent to an exposure of 4145 DAC-hours, will deliver a committed effective dose of 330 mrem. The predicted $^{239/240}Pu$ excretion in feces is 2.2 pCi compared to the 0.022 pCi observed. The plot of observed and predicted urinary excretion is presented in Figure 12 below.

Figure 12. Predicted and observed urinary excretion assuming an inhalation intake of 52.8 nCi of Type S weapons grade plutonium.



Assuming an acute inhalation intake of Type SS (“Super S” or highly insoluble) weapons grade plutonium on 7/1/01, the intake is estimated to be 333 nCi. This intake, which is equivalent to an exposure of 26171 DAC-hours, will deliver a committed effective dose of 3956 mrem. The predicted $^{239/240}$Pu excretion in feces is 5.6 pCi compared to the 0.022 pCi observed. The plot of observed and predicted urinary excretion is presented in Figure 13 below.

Figure 13. Predicted and observed urinary excretion assuming an inhalation intake of 333 nCi of Type SS weapons grade plutonium.



Over the 200-day time span in question, the predictions of all three intake scenarios are reasonably consistent with the observed urinary excretion. However, they lead to very different dose estimates. To select which model is most appropriate, we need to follow the urinary excretion over a longer time and look at other types of bioassay data. This individual received a routine chest count on 4/25/02, which did not detect any ^{241}Am above background. This effectively rules out the insoluble classes of plutonium so long as the material was aged plutonium[a]. In addition, in this case a single fecal sample was analyzed. The $^{239/240}$Pu content of this sample is most consistent with the assumption of Type M plutonium, which leads to a rather trivial dose estimate of 43 mrem.

Another important fact that supports the assumption of a Type M intake is that the Type S and SS intake scenarios predict extremely high exposures (4145 DAC-hours and 26171 DAC-hours, respectively). Exposures of this magnitude are inconsistent with any observed area air monitoring data, even the cumulative exposure for a whole year in the most highly contaminated rooms of FB-Line.

TIMS urine bioassay data, especially <u>one</u> routine TIMS urine bioassay result by itself, can lead to a variety of vastly different dose estimates depending on the solubility and isotopic composition of the plutonium that are assumed. Thus, if we routinely analyze urine samples by TIMS and results above the detection level are not uncommon, it would be best to collect and analyze fecal samples along with the urine samples (see the evaluation of OPS-2).

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[a] "Aged" means that enough time has passed to allow Am-241 to grow in to a useable level.

We may never know for sure, but even with all of the negative PAS data associated with OPS-6 this intake could have occurred during the study period. This raises a crucial point: PAS data cannot conclusively prove by itself that an intake did not occur. It is quite possible and perhaps even inevitable that workers can receive an intake that does not show up with PAS but does show up with bioassay. This type of discrepancy could arise for numerous reasons, three of which are:

- The worker who receives an inhalation intake while not wearing the PAS (see the narrative for OPS-12) or the PAS was not functional.
- The intake is by wound.
- The plutonium concentration of the air the PAS measured was not the same as the plutonium concentration of the air the person inhaled[a].

The last point highlights the fact that although PAS are generally considered to be more representative than area air monitors, they can provide inaccurate estimates of exposure. For example, NUREG/CR-4033[6] discusses an experiment where acute exposures were measured with two PAS, one attached to the right lapel and one to the left lapel. The exposures measured by the two PAS differed by a factor of five. The conclusion made here is that PAS are considered to be most accurate when the exposures are protracted over time and are fairly uniform in magnitude. Acute exposures, like those experienced during an incident, may be much less accurate.

Let us assume that the intake did not occur during the study period but rather was a historic intake[b]. The excretion of plutonium in the urine from historic intakes creates a background "noise" that complicates the evaluation of current and future excretion data. For example, if the urinary excretion is observed to rise we have to decide if we are looking at effects of analytical and biological variance or the effects of a new intake superimposed on historic intakes. The impressive detection levels achieved with TIMS do not help in situations like this and in fact can create problems by permitting us to observe historic intakes in more workers. In essence, the low detection level of TIMS transforms a "detection problem" into an "interpretation problem" -- now we have to explain what all of the positive data means. The presence of Type SS material in the workplace greatly complicates this task.

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[a] A bit of folk wisdom concerning this issue that is attributed to Roscoe Hall is that a PAS can measure only what a person does not inhale – all other interpretations are a leap of faith.
[b] In general, a historic intake is an intake that occurred sometime before the time span in question.

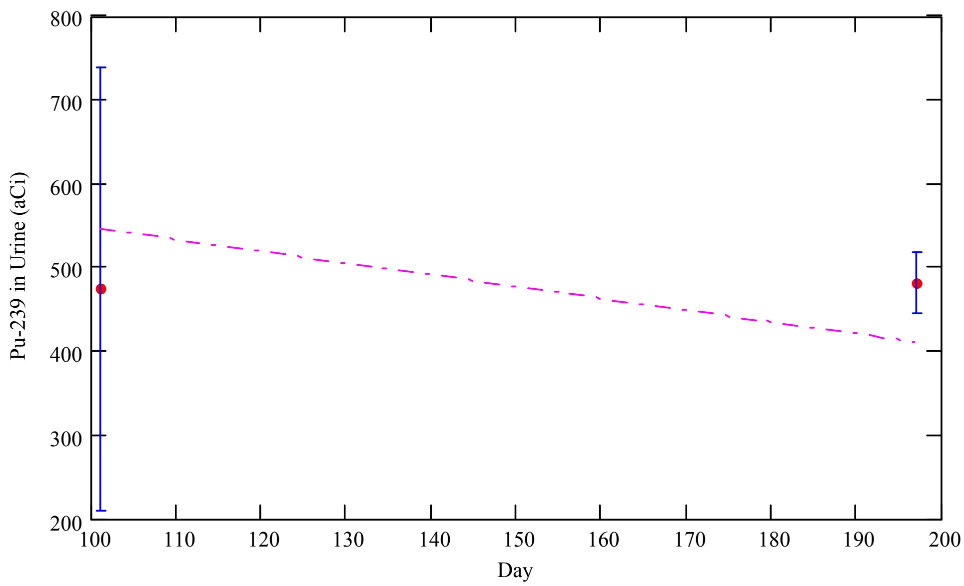
OPS-2
This operator used 147 filters in 140 days, recording a cumulative exposure of 33.5 DAC-hours. Urine and feces bioassay data for operator OPS-2 are presented below. The times of the samples are set relative to the 12/2/01 sample.

Table 2. Bioassay data for OPS-2. See Appendix A for a discussion of terminology.

Date	Time (days)	Nuclide	Sample Type	Result (pCi)	Ld (pCi)	2σ error (pCi)
7/14/2001	-141	Pu239	MS urine	0.000026	0.000300	0.000055
12/2/2001	0	Pu239	MS urine	0.000568	0.000300	0.000850
3/13/2002	**101**	**Pu239**	**MS urine**	**0.000475**	**0.000300**	**0.000265**
6/17/2002	**197**	**Pu239**	**MS urine**	**0.000482**	**0.000300**	**0.000037**

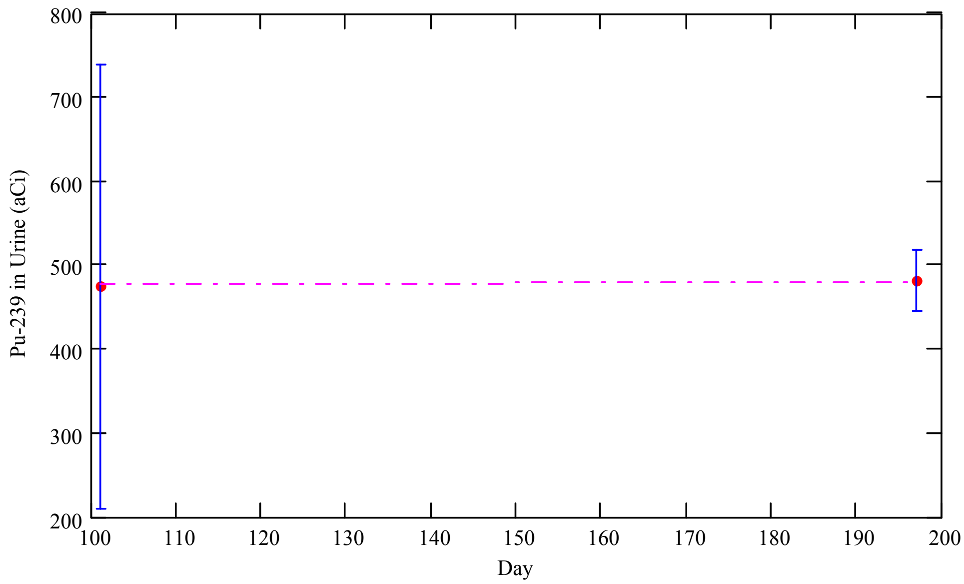
Assuming an acute inhalation intake of Type M (soluble) weapons grade plutonium, the intake is estimated to be 0.64 nCi. This intake, which is equivalent to an exposure of 50 DAC-hours, will deliver a CED of 16 mrem. The predicted $^{239/240}$Pu excretion in feces is 0.005 pCi. The plot of observed and predicted urinary excretion is presented in Figure 14 below.

Figure 14. Predicted and observed urinary excretion assuming an inhalation intake of 0.64 nCi of Type M weapons grade plutonium.



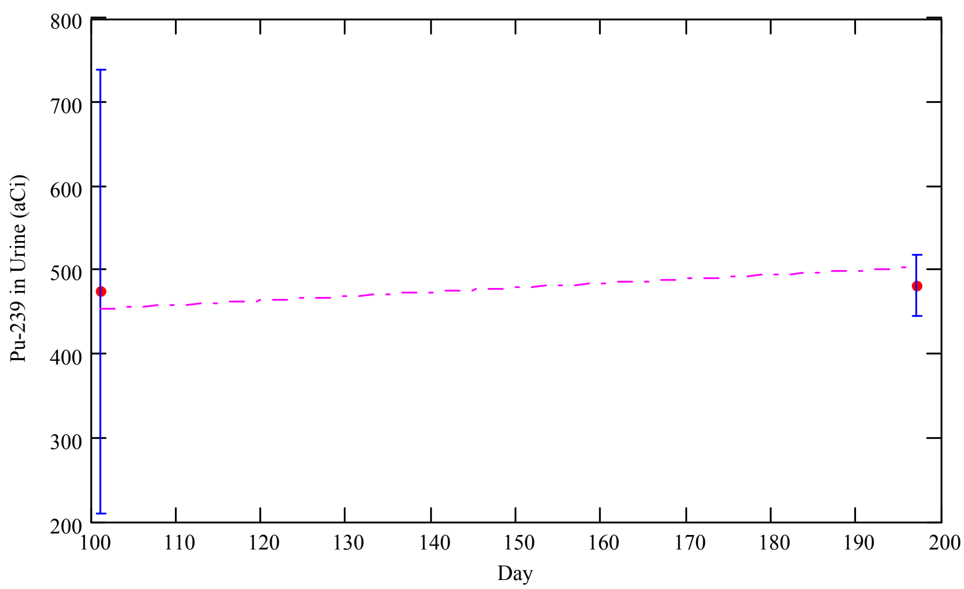
Assuming an acute inhalation intake of Type S (insoluble) weapons grade plutonium, the intake is estimated to be 24.3 nCi. This intake, which is equivalent to an exposure of 1906 DAC-hours, will deliver a CED of 152 mrem. The predicted $^{239/240}$Pu excretion in feces is 0.334 pCi. The plot of observed and predicted urinary excretion is presented in Figure 15 below.

Figure 15. Predicted and observed urinary excretion assuming an inhalation intake of 24.3 nCi of Type S weapons grade plutonium.



Finally, assuming an acute inhalation intake of Type SS (extremely insoluble) weapons grade plutonium, the intake is estimated to be 165 nCi. This intake, which is equivalent to an exposure of 12952 DAC-hours, will deliver a committed effective dose of 1958 mrem.

Figure 16. Predicted and observed urinary excretion assuming an inhalation intake of 165 nCi of Type SS weapons grade plutonium.



The predicted $^{239/240}$Pu excretion in feces is 0.733 pCi. The plot of observed and predicted urinary excretion is presented in Figure 16.

Unlike OPS-6, in this case we do not have a fecal sample to help choose a lung solubility type but we do have PAS data during the time of interest. Both the PAS data and the area air monitoring data[a] seem to support the assumption of Type M plutonium, but a follow-up fecal sample and TIMS urine are required to confirm this assumption.

RPD-2

Inspector RPD-2 had the fourth highest cumulative exposure (41 DAC-hours) according to the PAS monitoring, used respiratory protection extensively, and used the highest number of PAS filters (328) in the second highest number of days worked (151). Even with all of this activity and resulting exposure, all of his bioassay data, including three TIMS urine samples and four fecal samples, supports the contention that he did not receive any intakes of plutonium. This case is the converse of OPS-6 and once again points out the fact that PAS data and bioassay data do not necessarily lead to the same conclusions.

OPS-10

This operator was involved in two incidents while wearing a PAS. This gives us an opportunity to compare PAS with area air monitoring and bioassay.

10/3/01 MLM Corridor Incident

On 10/3/01 OPS-10 and another worker were in a maintenance corridor while waste was being removed from a room. A CAM alarmed in the corridor, indicating an exposure of 18.1 DAC-hours. While neither was wearing respiratory protection, OPS-10 was wearing a PAS. An exposure of 7.5 DAC-hours[b] was measured with the PAS. Two area air monitors located near the scene of the event measured exposures of 51 DAC-hours and 44 DAC-hours.

Both operators were placed on a special bioassay program consisting of two 24-hour urine samples and a fecal sample. The fecal sample of OPS-10 contained 11 pCi of $^{239/240}$Pu whereas the urine sample did not contain any plutonium activity above the detection level. An inhalation intake of 116.4 pCi of insoluble plutonium and americium was calculated[c] from the lone fecal sample, which represents an exposure of 48.5 DAC-hours. These results are summarized in Table 3 below.

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[a] Again, note that extremely high exposures that are predicted by the Type S and SS assumptions.

[b] Note that the DAC used in these calculations is 2E-12 µCi/cc, which is based on the dose to bone surfaces from soluble Pu-239. The usual rule of thumb that 1 DAC-hour = 2.5 mrem CEDE will therefore not hold for these evaluations.

[c] Calculated using special bioassay and standard ICRP 30 models per site procedures.

Table 3. Comparison of intake and exposure for the 10/3/01 incident calculated with bioassay data, PAS data, and air monitoring data.

	Intake (pCi)	DAC-Hr
PAS	18.0	7.5
A011	43.7	18.1
F087	122.1	50.9
bioassay	116.4	48.5

Although it appears as if the area air samplers agree with the bioassay data better than the PAS, without the associated uncertainties[a] we really cannot draw such a conclusion (for all we know the intakes and exposures may be statistically the same). The same warning should also be heeded when the PAS agrees with the bioassay data better than the area air samplers.

It is interesting to note that although none of the TIMS urine data exceeded the ^{239}Pu decision level of 300 aCi, there was an increase between the 9/23/01 and 11/29/01 samples that persisted in the 2/18/02 and 5/29/02 samples. The TIMS urine data and fecal data are consistent with an inhalation intake[b] of 320 pCi of soluble weapons grade plutonium on 10/3/01.

5/12/02 MLM Corridor Incident

On 5/12/02 OPS-10 and another worker were bagging out waste. They were both wearing fresh-air hoods. Later, OPS-10 was receiving the waste from the room while standing in the corridor. Approximately 45 minutes after the workers left the area a CAM alarmed in the maintenance corridor (posted as a CA/Non-ARA), which is right outside of waste room. OPS-10 was wearing a PAS while working in waste room and the corridor[c]. An exposure of 12.0 DAC-hours was measured with the CAM and 33.3 DAC-hours with the PAS. Both workers were placed on a special bioassay program consisting of a 24-hour urine sample and a fecal sample. The fecal sample of OPS-10 contained 0.42 pCi of $^{239/240}$Pu whereas the urine sample did not contain any activity above the detection level. An intake[d] of 5.5 pCi of plutonium and americium was calculated from the lone fecal sample, which represents an exposure of 2.3 DAC-hours. These results are summarized in Table 4 below.

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[a] The uncertainty in the exposure must contain the uncertainty in estimating the exposure from the air sampling results, not just the uncertainty in the air sampling results.

[b] Calculated using ICRP 66/67 biokinetic models.

[c] In this case the PAS filter was screened within hours of the event using the Harwell AB-14 counter, which is a new type of counter capable of discriminating against radon/thoron daughters. However, the final count was performed on the Tennelec.

[d] Calculated using special bioassay and standard ICRP 30 models per site procedures.

Table 4. Comparison of intake and exposure for the 5/12/02 incident calculated with bioassay data, PAS data, and air monitoring data.

	Intake (pCi)	DAC-Hr
PAS	80.0	33.3
CAM	28.8	12.0
bioassay	5.5	2.3

In this case the intake estimated with PAS was higher than the intake estimated with bioassay data, which is just the reverse of the 10/2/01 incident. In both incidents the official intake was estimated from a single fecal sample. A positive result from such a sample is probably a good indicator that an intake of some sort occurred. However, if one considers the uncertainties inherent in the process of calculating an intake from a single fecal void, one would probably conclude that the intake estimate should be considered to be semi-quantitative at best. Nevertheless, the intakes calculated from the bioassay data were assigned to the operator.

This practice is driven by federal rule 10CFR835.209(b)(3), which dictates that bioassay shall be used to estimate an internal dose unless the internal dose based on air monitoring data can be demonstrated to be as or more accurate. Technically speaking, none of these intake estimates can be demonstrated to be more accurate than any of the others because the true value of the intake is not (and probably never will be) known[a]. In practice, an intake estimated from air monitoring data is assigned to a worker only if the air sampler is representative and the intake cannot be refuted by bioassay. Examples of this situation include

- An incident occurs and prescribed samples are not collected, are not collected properly, or the minimum detectable dose for the bioassay method exceeds 100 mrem.
- A PAS used to monitor recurring low-level exposures to a worker indicates a cumulative intake that is below the minimum detectable intake achievable with the routine bioassay program.
- Occupational exposures to radon and thoron[b].

The situation becomes less problematic for larger intakes where there is usually a wealth of different types of bioassay data in addition to the air monitoring data. In these cases the best intake estimate is usually deemed to be the one that is most consistent with all of the observed data.

RPD-4

A subset of the bioassay data for inspector RPD-4 is shown in Table 5 below. Recall that the radiological control inspectors who participated in the study submitted four routine fecal

[a] The accuracy of a measurement is typically defined to be how close the measurement is to the true value. Thus, if the true value is not known, the accuracy of the measurement cannot be defined.

[b] Short-lived radioactive progeny that cannot be readily detected by bioassay deliver the majority of the dose resulting from exposures to radon and thoron.

samples. Note that while the 3/13/02 fecal sample and TIMS urine sample were positive for ^{239}Pu, the follow-up samples submitted two months later were less than the decision level.

Table 5. Bioassay data for RPD-4. See Appendix A for a discussion of terminology.

Date	Time (days)	Nuclide	Sample Type	Result (pCi)	DL (pCi)
3/13/02	**255**	**Am241**	**feces**	**0.081081**	**0.009910**
3/13/02	255	Pu238	feces	0.015766	0.030180
3/13/02	**255**	**Pu239**	**feces**	**0.244595**	**0.021171**
5/12/02	315	Am241	feces	0.002703	0.013063
5/12/02	315	Pu238	feces	0.011261	0.029730
5/12/02	315	Pu239	feces	0.005405	0.029730
3/13/02	**255**	**Pu239**	**MS urine**	**0.001025**	**0.000300**
5/10/02	313	Pu239	MS urine	0.000012	0.000300

A subset of the PAS data for RPD-4 shown in Figure 6 below shows that there were no significant exposures during the time span of 3/6/02 to 3/14/02. However, on 3/12/02 this inspector handled a filter that had on it approximately 10,000 pCi of alpha activity (he was wearing a PAS at the time). Nevertheless, the inspector was instructed to submit the routine urine and fecal samples the next day as scheduled. We could have postponed the collection of the routine samples in this case, but we decided to collect them anyway to “see what happened.”

Table 6. Summary of PAS data for RPD-4. See Appendix A for a discussion of terminology.

Respiratory Protection	Start Time	Stop Time	Time Days	Exposure (DAC-Hr)	Exposure with PF
Plastic Hood	3/6/02 7:20 PM	3/6/02 9:30 PM	249	0.53	0.53
Plastic Hood	3/6/02 10:00 PM	3/6/02 11:30 PM	249	-0.29	-0.29
Plastic Hood	3/7/02 1:00 AM	3/7/02 5:00 AM	249	0.96	0.96
None	3/8/02 7:30 PM	3/9/02 6:00 AM	251	-0.31	-0.31
None	3/12/02 7:20 AM	3/12/02 6:30 PM	254	-0.30	-0.30
None	3/13/02 11:30 AM	3/13/02 6:00 PM	255	0.13	0.13
None	3/14/02 7:00 AM	3/14/02 12:00 PM	256	0.13	0.13
Plastic Hood	3/14/02 12:00 PM	3/14/02 2:00 PM	257	0.13	0.13
None	3/14/02 2:30 PM	3/14/02 6:30 PM	257	0.13	0.13

The key point here is that the inspector was working in radiological buffer areas shortly before submitting the fecal sample and TIMS urine sample. This can result in “false positive” results for two reasons. First, the detection level for plutonium contamination on a worker is on the order of several hundred pCi. If we attempt to have a worker contaminated to these levels submit a sample that will be analyzed for levels of plutonium a million times lower, we are bound to experience significant problems with cross contamination. The presence of “nonmetabolized" plutonium in an ultra-sensitive bioassay sample is very difficult to discern and can be extremely misleading. Second, a recent insignificant intake will produce bioassay results that are (in the short term) indistinguishable from a significant intake that occurred in the more distant past. For example, the 3/13/02 bioassay results (by themselves) are consistent with an intake of highly insoluble plutonium that would deliver a dose on the order of 5 rem. The results of the follow-up samples proved that this was not the case and that the dose was trivial.

The participants of the study were urged to avoid work in radiological buffer areas for as long as possible before submitting the urine and fecal samples, which must be considered to be a major factor in the six-fold reduction in the number of positive fecal samples observed between the 1992 and 2002 studies. This case is a clear example of what can happen if the demands of personal and production schedules prevent a worker from avoiding RBA access before submitting TIMS urine samples and fecal samples.

OPS-7

The 11/13/01 PAS filter for operator OPS-7 was counted on 11/16/01 and was reported as 120 DAC-hours. The sample should have been screened with the Harwell AB-14, but this counter did function properly until about March 2002. The operator initially indicated that he did not wear a full-face respirator that day, but a review of the records indicated that he was issued a respirator and that he entered an ARA in which an exposure of 84 DAC-hours was measured on that day. The operator was placed on a special bioassay program because of the apparent uncertainty about the respirator and the fact that he used the same PAS filter for monitoring exposures with and without a respirator[a].

No intake was assigned as a result of this incident, but this case illustrates two operational points. First, to obtain the greatest benefit from a PAS the filter must be screened on the day it is used. This permits the prompt investigation of any potential over exposures and allows timely follow-up actions like bioassay to be taken. Second, using a PAS with a full-face respirator can pose difficulties because the PAS filter must be changed when the respirator is put on or taken off. This practice, which ensures that the appropriate protection factor is applied to the measured exposure, is problematic for workers on maintenance rounds and fire watches who go in and out of areas requiring respiratory protection.

[a] Workers must change PAS filters when they take off or put on a full-face respirator so that the appropriate protection can be applied to the measured exposure.

Recommended Internal Dose Monitoring Program

There was clearly a preferred outcome to this study from the beginning, namely that the TIMS urine bioassay be adopted for use in FB-Line rather than the fecal bioassay or PAS. Fecal bioassay was not preferred because, almost universally, workers have a strong aversion to the collection of fecal samples. PAS was not preferred because workers and management generally view it as being intrusive, labor intensive, and inconvenient. On the other hand, because workers already submit routine urine samples, the TIMS urine bioassay would place no additional burdens or requirements on the workers. These preferences were considered during the formulation of these recommendations.

To establish a cost-effective monitoring program it is necessary to restrict the enhanced bioassay program (EBP) to those workers with a reasonable potential for exposure to insoluble plutonium. To do this, all work controlled by RWPs (both job-specific and standing) or procedures should be classified according to the potential for exposing workers to insoluble forms of plutonium. The magnitude of this potential is a function of

- The quantity of unencapsulated plutonium present.
- The fraction of the plutonium that is insoluble.
- The nature of the work.

Exactly what constitutes reasonable potential is ultimately a matter of professional judgment, but a clear indicator for requiring an EBP is the use of respiratory protection in an area where a material like plutonium oxide is present in large quantities. The EBP will consist of an annual 24-hour urine sample that is collected after an "extended" RBA access restriction and then analyzed by alpha and mass spectrometry. The term "extended" refers to a weekend at a minimum, but bear in mind that the longer a worker stays out of an RBA the lower are his chances of having a false positive as a result of cross contamination or a small recent intake.

Ideally, all workers who sign in on an RWP requiring an EBP would participate in the program. However, because of the relatively high expense of TIMS analysis, selection criteria may be applied to select the workers at highest risk of an exposure. Typically, this will be the workers who spend the most time working under these RWPs (highest occupancy time).

Action levels for the EBP samples are:

- If an EBP sample contains more than 300 aCi of plutonium-239 but less than 500 aCi, a follow-up urine sample will be requested. The follow-up samples must be submitted after an extended absence from the RBA and must be submitted within 30 days of the request. The worker may return to work after completion of the follow-up program, but a positive follow-up may require RBA access restrictions.

- If an EBP sample contains more than 500 aCi of plutonium-239 but less than 45,000 aCi, follow-up urine and fecal samples will be requested. The follow-up samples must be submitted after an extended absence from the RBA and must be submitted within 30 days of the request. The worker may return to work after completion of the follow-up program, but a positive follow-up may require RBA access restrictions.

- If an EBP sample contains more than 45,000 aCi of plutonium-239, follow-up urine and fecal samples will be requested. The follow-up samples must be submitted after an extended RBA access restriction and must be submitted within 14 days of the request. Once the request is made, the worker may not return to work until the dose has been evaluated.

There is an existing site requirement that any routine urine sample that contains more than 45,000 aCi (0.1 dpm) of plutonium will result an immediate RBA access restriction until the dose is evaluated. The results of the follow-up program, which are handled on a case-by-case basis, may indicate the need for additional samples and work restrictions.

The RBA access restrictions required with a TIMS urine bioassay program pose a potentially significant complication, which goes something like this:

- The worker submits a routine TIMS urine sample. RBA access restrictions are required before sample is submitted. There is no minimum time for the restrictions, but the probability of a false positive must be assumed to decrease with time away from the RBA.
- The routine TIMS urine sample is reported to be above the 500 aCi action level approximately 60 days after it is submitted (this is the standard turn-around-time for these samples). During this 60-day period the worker will probably be in the RBA and could have an intake of plutonium, which could complicate matters further.
- The worker must arrange another RBA access restriction period before submitting the follow-up samples. Again, the longer he is away from the RBA the lower is the chance of a false positive due to cross contamination or recent small intake.
- If the follow-up sample is positive, the worker is restricted from RBA access until the case is resolved.

Thus, the EBP could lead to an excessive number of unnecessary work restrictions if workers are exposed to soluble plutonium and/or do not allow an appropriate clearance time before submitting urine and fecal samples[a]. If an EBP based on occupancy time becomes prohibitively disruptive, participation in the EBP can be based on cumulative DAC-hour exposure. In this approach, the DAC-hours are tracked for workers on the "reasonable potential" RWPs. This means that DAC-hour tracking takes place only for work performed on RWPs with a reasonable potential for exposure to insoluble plutonium. Once a worker exceeds a cumulative exposure of 100 DAC-hour[b] in a calendar year he is placed on the EBP. In this situation, the EBP is indicated because the worker is now "likely" to exceed 100 mrem and a bioassay program capable of demonstrating compliance with the 5 rem TEDE limit is required.

The dose from all measurable exposures will be assigned to the worker in accordance with the site PAS procedure. In accordance with existing site procedures, exposures of more than 8 DAC-hours in a day will trigger a special bioassay program.

[a] Assuming, of course, that they are not really getting significant intakes of insoluble plutonium.
[b] Assuming 100 DAC-hours = 100 mrem (see Appendix B).

Implementation Issues
Perhaps the most difficult and important part of implementing the EBP is the accurate identification of workers who are at risk of exposure to Type SS plutonium. The accurate identification of workers is important because only by limiting the EBP to these workers can we hope to afford the cost of the program. Identifying these workers is difficult for two main reasons. First, the 9/1/99 FB-Line incident demonstrated that very insoluble forms of plutonium could be created under (appropriate conditions) at relatively low temperatures. This means that very insoluble Type SS material may not be confined to easily identified areas such as furnaces. In addition, the spontaneous conversion of soluble plutonium to insoluble plutonium in the workplace has been reported in the literature[7]. Second, we seem to have reasonably good knowledge of the locations and chemical forms of macroscopic (kilogram) quantities of plutonium. However, this knowledge does not always extend to the microscopic (microgram) level, which is more than enough material to deliver significant doses to workers. Efforts are being made to develop the capability of performing in-vitro lung solubility tests. Once available, these tests will help us to positively identify locations where very insoluble forms of plutonium are present.

Cost
The cost of any monitoring program will be determined to a large degree by the number of workers who participate in the program. The size of the population that will be monitored in FB-Line is not known at this time, but for the purpose of this discussion we will assume that

- 100 workers will participate.
- TIMS urine analysis costs $1700 per sample.
- There is a 50% resample rate for urine samples.
- Fecal analysis costs $2500 per sample.
- There is a 10% sampling rate for fecal samples.

The annual cost of a routine TIMS program would then be approximately

$$(150 \times \$1700) + (10 \times \$2500) = \$280,000.$$

Placing the same 100 workers on a PAS monitoring program for *all entries into the FB-Line RBA* would be approximately $407,000 per year. The highly selective use of PAS as described above could reduce this cost significantly. For the purpose of this discussion, let us assume that the PAS Option, including any TIMS urine and fecal samples required as follow-up, would have the same annual cost as the routine TIMS urine program. The cost difference between the two programs then boils down to the lost productivity due to using a PAS versus the lost productivity due to RBA access restrictions from the TIMS urine program. Ultimately, the best choice will be determined by the number of positive TIMS results that are generated in the EBP.

References

[1] Caldwell, Roger , *Evaluation of Radiation Exposure* Health Physics Operational Monitoring, Volume 1 (New York: Gordon and Breach) 1972.
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[3] *Type B Accident Investigation Report of the September 1, 1999 Plutonium Intakes at the at the Savannah River Site FB-Line*, February 2000.
[4] *A Dissolution Study of Plutonium Aerosols from the Savannah River Site*, Lovelace Respiratory Research Institute, June 2001.
[5] Mandel, J. *The Statistical Analysis of Experimental Data* (New York: Dover) 1984.
[6] Ritter, P. D. et al. *The Role of Personal Air Sampling in Radiation Safety Programs and Results of a Laboratory Evaluation of Personal Air-Sampling Equipment*, NUREG/CR-4033, December 1984.
[7] Moody, J. C. et al. *Biokinetics of Three Industrial Plutonium Nitrate Materials: Implications for Human Exposure* Radiation Protection Dosimetry (53) 169-172, 1994.

Appendix A. Summary of PAS and Bioassay Data for Individual Workers

The results of PAS monitoring, chest counting, and in-vitro bioassay performed during the study for the 21 participants are summarized in this appendix. More detailed information on the results of the PAS monitoring program is provided in a separate report[a].

Urine and Feces Bioassay Results

The results[b] for all urine and fecal samples collected during the time period of 1/1/01 to 10/1/02 are presented in this appendix. With reference to the tables, note the following:

- *Work Date* is the last day the person entered an RBA prior to submitting the associated routine fecal sample. Special fecal samples do not have a *Work Date* because they are collected in response to an incident.
- *Date* is the date the sample was collected (fecal sample) or started (urine sample).
- *AS urine* refers to urine analyzed at SRS by alpha spectrometry.
- *MS urine* refers to urine analyzed by thermal ionization mass spectrometry (TIMS) at LANL.
- *Time* refers to the number of days elapsed since 7/1/01, which is the starting date of the study. A negative time means that the sample was collected before 7/1/01.
- L_d is the detection level, i.e., the level above which a sample is considered to contain activity above background (it is "positive"). Results above the decision level are presented in bold type.
- *2s error* is the analytical uncertainty in the reported result. This uncertainty does not include the uncertainty due to biological processes such as excretion rate.
- *Pu239* reported for an AS measurement refers to the sum of Pu-239 and Pu-240 activities. *Pu239* reported for an MS measurement refers to Pu-239 activity only.
- Activities are reported in units of pCi with six decimal places. This format, which often implies a precision that is not warranted[c], was used so that one can read the result from the right to give units of aCi or from the left to give units of pCi. For example, 0.000300 pCi is 300 aCi.
- *LIA* or "lost in analysis" means that the result of the analysis did not pass minimum quality control criteria and that no result is reported.

Chest Counts

Chest counts were not specially arranged for participants of the study. Therefore, participants who normally do not receive routine chest counts did not receive any chest counts during the study. All chest counts are 30-minute routine counts unless otherwise noted.

[a] *PAS Results from the 2002 Study in FB-Line*, ESH-HPT-2002-00170.
[b] Except for the results of alpha spectrometry performed by LANL.
[c] No difficulties should arise from this practice because the uncertainties in the results are presented.

PAS Results

The exposures measured by the PAS monitoring program are given in terms of DAC-hours. An exposure of 1 DAC-hour is equivalent to spending one hour in an atmosphere of 1 DAC of plutonium[a]. For reference, an exposure of 100 DAC-hours is assumed to deliver a committed effective dose equivalent of 100 mrem (see Appendix H). The exposure in DAC-Hr is calculated as shown below:

$$DAC - hour = \left[\frac{X\ pCi}{2.4\ pCi}\right]\left[\frac{20000\,mL/\min}{F\ mL/\min}\right]$$

where

X = the alpha activity on the lapel filter
F = the mean flow rate of the PAS pump

For example, if the alpha activity on the filter is 0.7 pCi and the mean flow rate is 3982 mL/min, the exposure in DAC-hours is

$$DAC - hour = \left[\frac{0.7\ pCi}{2.4\ pCi}\right]\left[\frac{20000\,mL/\min}{3982\,mL/\min}\right] = 1.46\,DACHr$$

The significance of the exposures may be measured by four different methods:

1) Exposures measured with a single filter may be compared to a 1 DAC-hour decision level. In other words, a single exposure greater than 1 DAC-hour is considered to be significantly different than background[b] (it is "positive").
2) All exposures, both above and below zero, may be summed to give a cumulative exposure for the study period. We can then calculate a decision level for the cumulative exposure. This approach is applied in two different ways:
    a) Exposures with no protection factor (PF) applied for full-face respirators.
    b) Exposures with a PF of 50 applied for full-face respirators.
3) All exposures less than the decision level are ignored and the remaining results summed. The decision level is applied before the protection factor in this approach.

Method 1 is considered to be appropriate for deriving action levels for responding to a particular PAS result. For example, a special bioassay program is triggered by a PAS result of more than 8 DAC-hours in a day. It is good to know that this action level is statistically significant, i.e., it is above the decision level. Although results for Methods 2a, 2b, and 3 are given, Method 2b is considered to be the best approach for determining annual cumulative exposures. The cumulative exposures calculated by Method 2b are considered to be statistically significant[c] (i.e., above background) for all workers except for OPS-6 and WSI-2.

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[a] DAC of 2E-12 µCi/cc.
[b] See Appendix E for a derivation of this decision level.
[c] See Appendix E for a derivation of this decision level.

The number of days PAS were worn by each worker, the number of PAS filters used, the cumulative exposure calculated by the three different methods are summarized in the following table.

	PAS Filters Used	Days Worked	Exposure (DAC-Hr)	Exposure with PF (DAC-hr)	Exposure with PF&DL (DAC-hr)
OPS-6	49	44	2.8	2.1	1.1
WSI-2	43	43	2.1	2.1	2.1
WSI-3	34	33	7.2	7.2	7.4
WSI-1	58	56	10.8	10.8	9.1
OPS-9	86	74	24.6	11.8	6.6
OPS-11	74	74	18.9	15.8	9.1
RPD-1	67	56	26.1	16.4	13.0
RPD-4	143	94	39.2	23.0	10.6
OPS-5	140	116	29.5	25.0	13.9
OPS-12	103	102	26.0	25.9	14.1
OPS-13	127	113	27.8	26.4	18.7
RPD-5	159	133	31.8	26.4	19.8
OPS-7	163	120	169.8	28.3	23.0
OPS-1	148	142	32.7	29.0	20.5
OPS-4	149	142	32.2	31.3	16.8
OPS-2	147	140	45.4	33.5	22.0
OPS-8	250	155	84.8	40.0	26.3
RPD-2	328	151	62.1	41.1	28.1
RPD-3	267	128	62.5	41.2	24.8
OPS-3	154	133	49.6	43.6	32.8
OPS-10	102	97	65.6	65.8	59.2

A review of the number of days worked by the participants during study was performed[a] (see the table below). The minimum and maximum workdays (shifts) calculated for each participant consider the actual start dates for the lapel air sampling, work schedule (either shift or days and included the temporary shifts worked in the first part of the year), vacation days, and training days. Although a 7/1/2001 start date is used for the program, no workers started that early. Actual start dates for most ranged from late July to mid September depending on shift breaks and when baseline samples were collected. To determine the number of vacation days it was assumed that each worker took a week of vacation in the last half of 2001 and a week in 2002. To determine the number of training days it was assumed 10% to 20% of their shifts would be spent in training, which

[a] This information is paraphrased from a memorandum sent from Roy Windham to Walt Sansot on 12/5/02.

are typical values for the site. Some participants worked overtime in the facility, but it would be difficult to go back and determine how many shifts.

ID	PAS Filters Used	Days Worked	Target Days Worked (Min/Max)		Comments
OPS-6	49	44	133	149	Operations FLM so number of filters is expected to be low compared to others. In addition, the individual was out of work and on work restrictions during the program, wh ich limited his number of collected samples.
WSI-2	43	43			
WSI-3	34	33			
WSI-1	58	56			For WSI these numbers seem reasonable based on their shift schedule and scheduled time of working in the FB-Line RBA. For security purposes providing more information on them may be a problem.
OPS-9	86	74	119	135	Questionable usage
OPS-11	74	74	119	135	Questionable usage
RPD-1	67	56	128	146	RPD FLM who was assigned to Works Management so number of filters is expected to be low compared to others.
RPD-4	143	94	91	107	Originally another RCO Inspector was scheduled to be a participant. When this Inspectors facility access status was restricted we elected to add RPD-4 to the program in October 2001. Because of his late start this number of filters and days is not unreasonable.
OPS-5	140	116	113	129	
OPS-12	103	102	117	133	This Operator is believed to have been out for a period of time or on work restrictions, which would have reduced the number of filters collected.
OPS-13	127	113	117	133	Operations FLM, so number of filters is expected to be low.
RPD-5	159	133	133	149	
OPS-7	163	120	117	133	
OPS-1	148	142	128	146	
OPS-4	149	142	128	146	
OPS-2	147	140	128	146	
OPS-8	250	155	133	149	
RPD-2	328	151	133	146	
RPD-3	267	128	128	146	
OPS-3	154	133	128	146	
OPS-10	102	97	113	126	Operations FLM so number of filters is expected to be low.

OPS-1

Bioassay Results

Work Date	Date	Time (days)	Nuclide	Sample Type	Result (pCi)	DL (pCi)	2σ error (pCi)
	2/28/2001	-123	Am241	AS urine	0.006149	0.007734	0.007410
	2/28/2001	-123	Pu238	AS urine	0.005797	0.008689	0.008234
	2/28/2001	-123	Pu239	AS urine	0.005793	0.008689	0.008225
7/20/01	**7/24/2001**	**23**	**Am241**	**feces**	**0.015369**	**0.005761**	**0.010995**
7/20/01	7/24/2001	23	Pu238	feces	-0.001704	0.021869	0.009851
7/20/01	7/24/2001	23	Pu239	feces	0.007662	0.019932	0.014108
	2/27/2002	241	Am241	AS urine	0.002703	0.008559	0.005856
	2/27/2002	241	Pu238	AS urine	0.001351	0.013514	0.006757
	2/27/2002	241	Pu239	AS urine	0.003153	0.009009	0.005856
	7/22/2001	21	Pu239	MS urine	0.000009	0.000300	0.000039
	12/1/2001	153	Pu239	MS urine	0.000085	0.000300	0.000079
	3/22/2002	264	Pu239	MS urine	0.000147	0.000300	0.000092
	6/1/2002	335	Pu239	MS urine	0.000091	0.000300	0.000041

Chest counts on 2/26/01 and 2/27/02. No activity above background was detected.

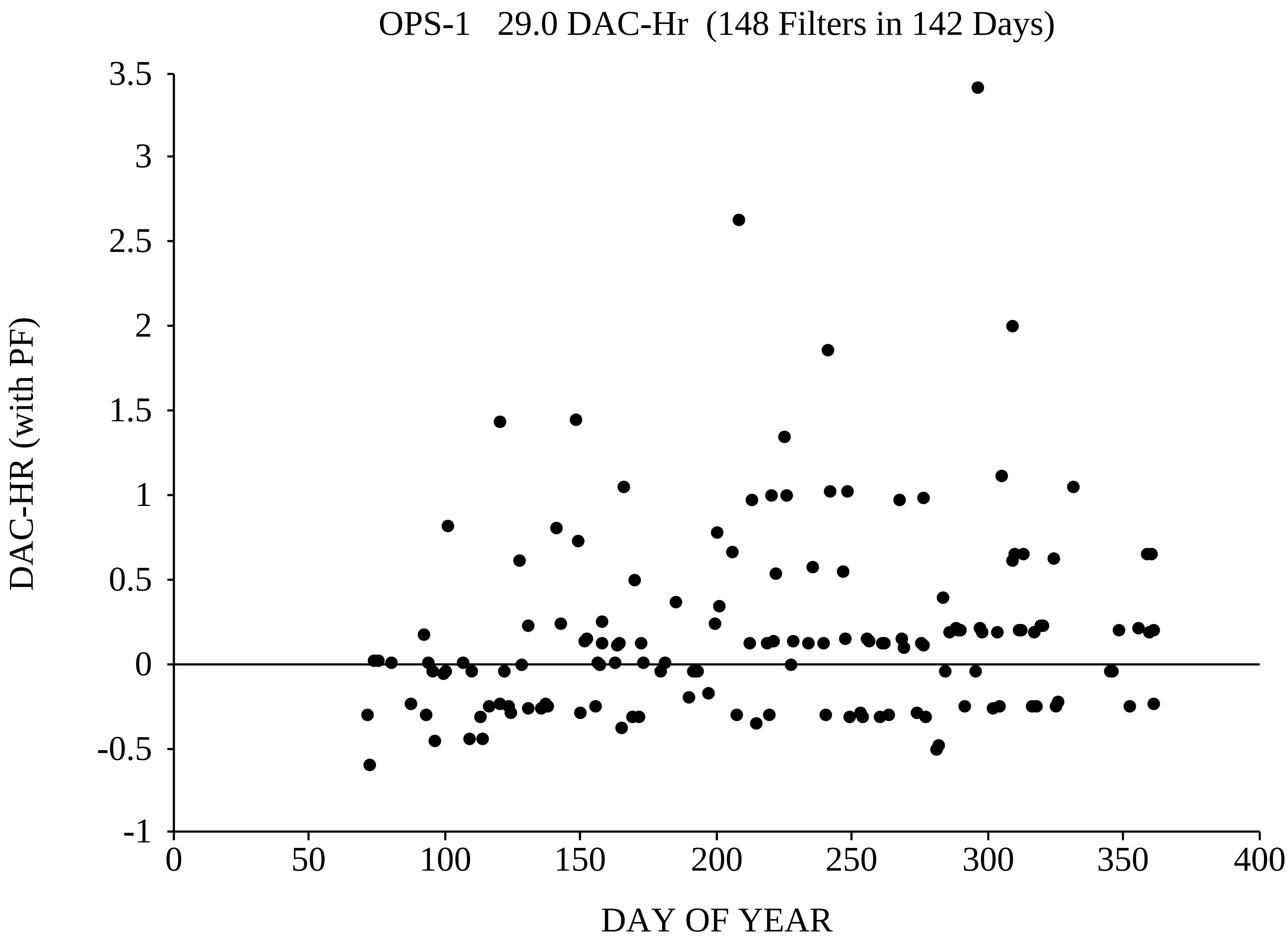
Summary of PAS Results

- 148 filters in 142 days
- Cumulative exposure of

  32.7 DAC-hours with no PF applied

  29.0 DAC-hours with PF applied

  20.5 DAC-hours with PF and DL applied



OPS-1 29.0 DAC-Hr (148 Filters in 142 Days)
DAC-HR (with PF)
DAY OF YEAR
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
0
50
100
150
200
250
300
350
400

OPS-2

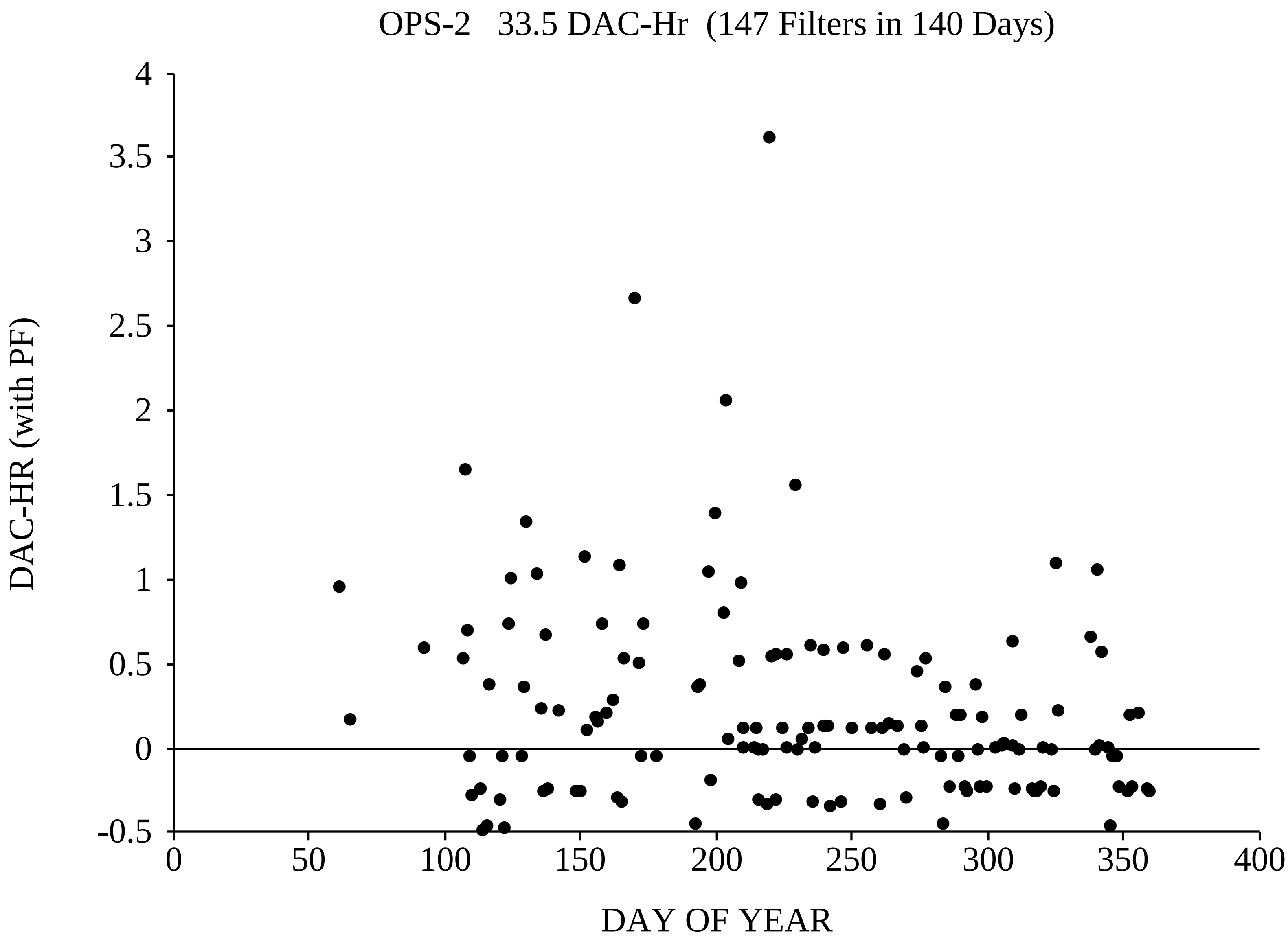
Bioassay Results

Work Date	Date	Time (days)	Nuclide	Sample Type	Result (pCi)	DL (pCi)	2σ error (pCi)
7/12/01	7/16/2001	15	Am241	feces	0.005464	0.027977	0.016649
7/12/01	7/16/2001	15	Pu238	feces	0.002918	0.018333	0.013063
7/12/01	**7/16/2001**	**15**	**Pu239**	**feces**	**0.032072**	**0.015527**	**0.021662**
	12/20/2001	172	Am241	AS urine	0.000000	0.015766	0.007207
	12/20/2001	172	Pu238	AS urine	0.000000	0.011261	0.000000
	12/20/2001	172	Pu239	AS urine	0.000000	0.011261	0.000000
	7/14/2001	13	Pu239	MS urine	0.000026	0.000300	0.000055
	12/2/2001	154	Pu239	MS urine	-0.000568	0.000300	0.000850
	3/13/2002	**255**	**Pu239**	**MS urine**	**0.000475**	**0.000300**	**0.000265**
	6/17/2002	**351**	**Pu239**	**MS urine**	**0.000482**	**0.000300**	**0.000037**

Chest count on 12/20/01. No activity above background was detected.

Summary of PAS Results

- 147 filters in 140 days
- Cumulative exposure of
  45.4 DAC-hours with no PF applied
  33.5 DAC-hours with PF applied
  22.0 DAC-hours with PF and DL applied


OPS-2 33.5 DAC-Hr (147 Filters in 140 Days)
DAC-HR (with PF)
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
0
50
100
150
200
250
300
350
400
DAY OF YEAR

OPS-3

Bioassay Results

Work Date	Date	Time (days)	Nuclide	Sample Type	Result (pCi)	DL (pCi)	2σ error (pCi)
8/27/01	9/3/2001	64	Am241	feces	0.003604	0.010811	0.008559
8/27/01	9/3/2001	64	Pu238	feces	0.013514	0.019820	0.018919
8/27/01	9/3/2001	64	Pu239	feces	0.000000	0.019820	0.000000
	11/26/2001	148	Am241	AS urine	0.002703	0.008559	0.005856
	11/26/2001	148	Pu238	AS urine	0.006757	0.020270	0.013514
	11/26/2001	148	Pu239	AS urine	0.000000	0.013514	0.000000
	9/3/2001	64	Pu239	MS urine	-0.000048	0.000300	0.000057
	12/28/2001	180	Pu239	MS urine	0.000009	0.000300	0.000114
	3/8/2002	250	Pu239	MS urine	0.000041	0.000300	0.000083
	6/22/2002	356	Pu239	MS urine	0.000038	0.000300	0.000032

Chest count on 11/26/01. No activity above background was detected.

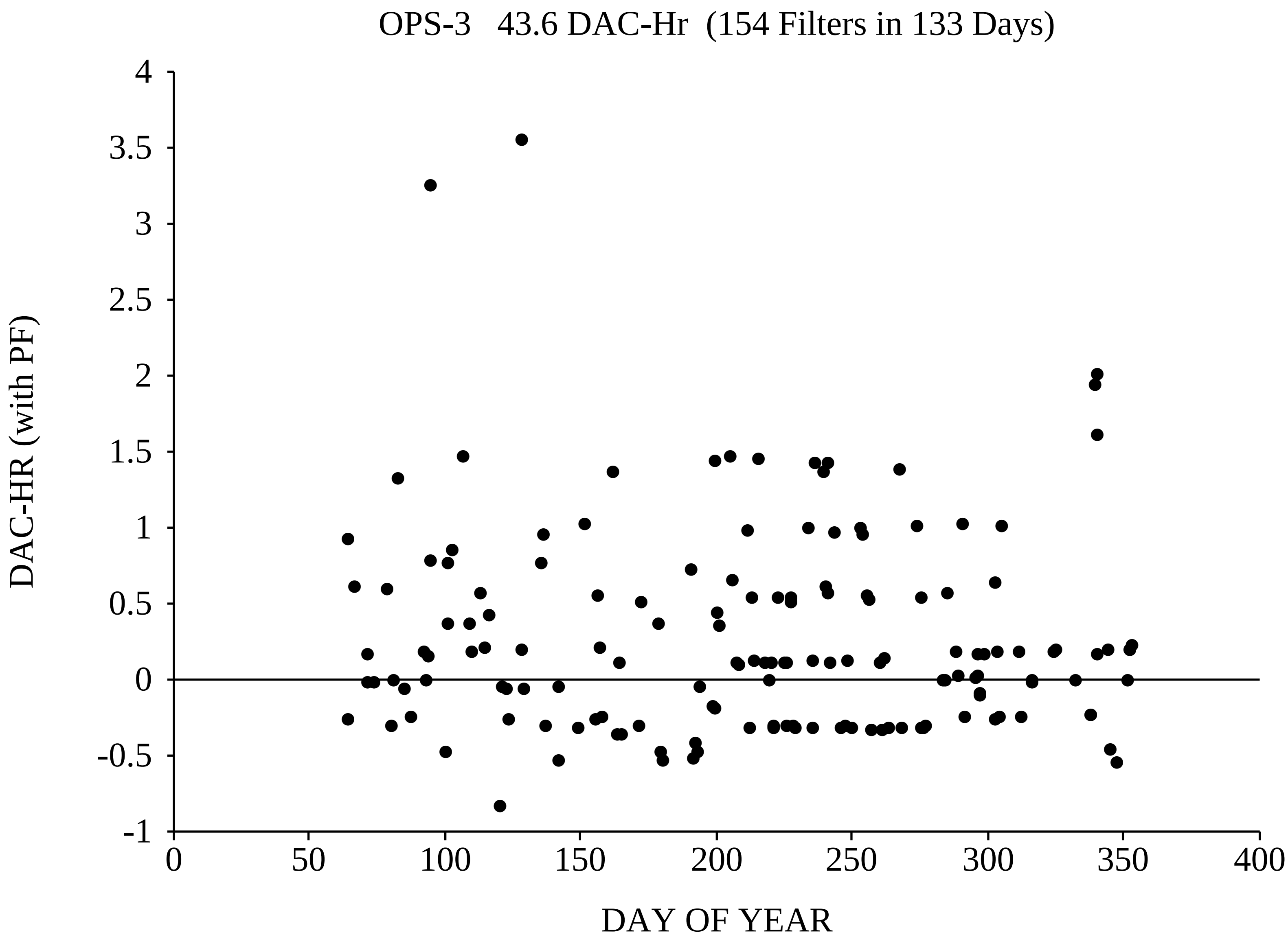
Summary of PAS Results

- 154 filters in 133 days
- Cumulative exposure of

  49.6 DAC-hours with no PF applied

  43.6 DAC-hours with PF applied

  32.8 DAC-hours with PF and DL applied


OPS-3 43.6 DAC-Hr (154 Filters in 133 Days)
DAC-HR (with PF)
DAY OF YEAR
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
0
50
100
150
200
250
300
350
400

OPS-4

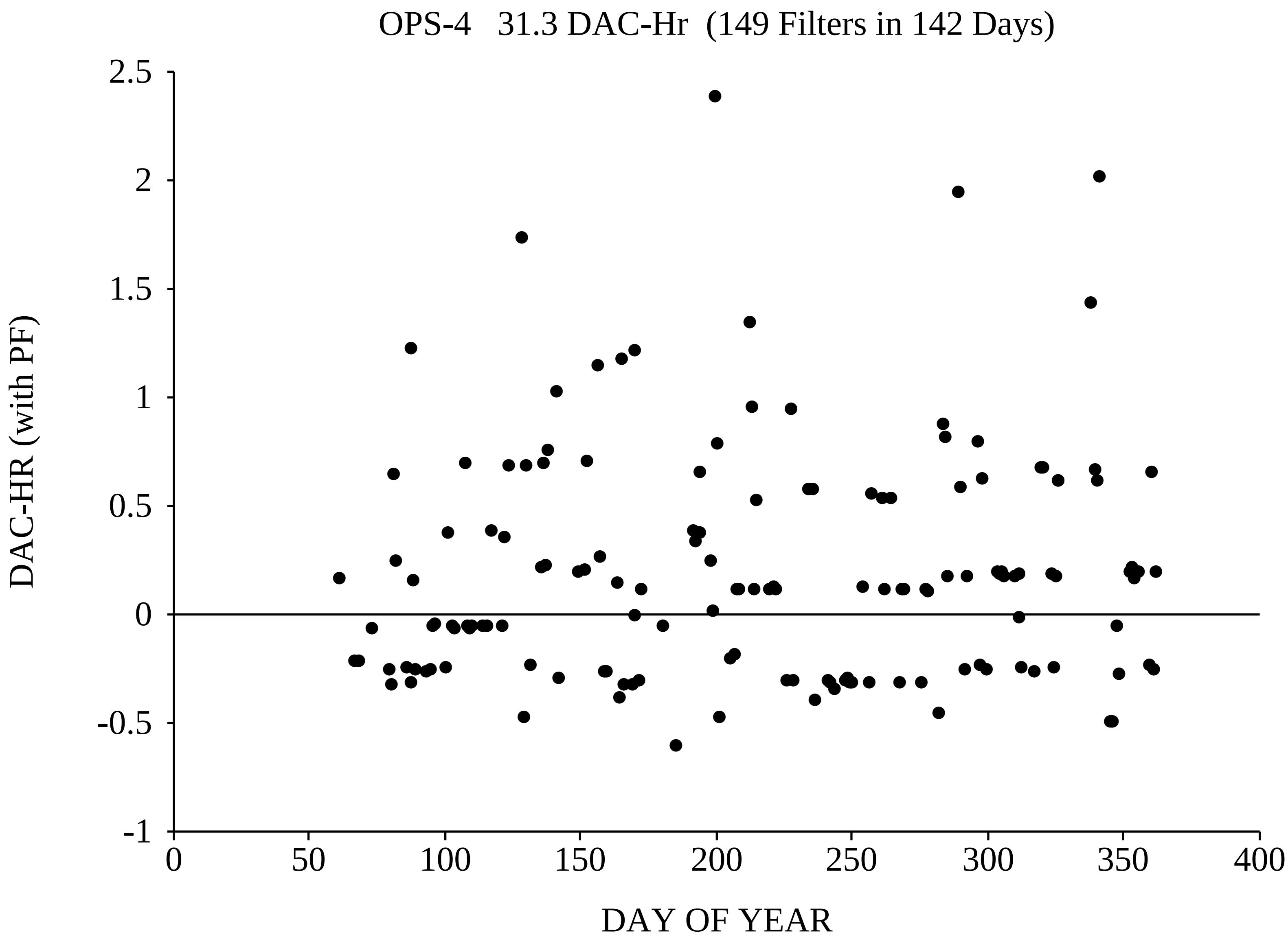
Bioassay Results

Work Date	Date	Time (days)	Nuclide	Sample Type	Result (pCi)	DL (pCi)	2σ error (pCi)
7/13/01	7/16/2001	15	Am241	feces	-0.002551	0.024342	0.005117
7/13/01	7/16/2001	15	Pu238	feces	-0.004139	0.022590	0.005905
7/13/01	7/16/2001	15	Pu239	feces	0.004411	0.022590	0.013450
	9/18/2001	79	Pu238	AS urine	0.000000	0.010811	0.000000
	9/18/2001	79	Pu239	AS urine	0.000000	0.010811	0.000000
	7/15/2001	14	Pu239	MS urine	0.000011	0.000300	0.000075
	12/5/2001	157	Pu239	MS urine	0.000273	0.000300	0.000092
	3/12/2002	**254**	**Pu239**	**MS urine**	**0.000638**	**0.000300**	**0.000756**
	5/14/2002	317	Pu239	MS urine	0.000138	0.000300	0.000069

Chest counts on 9/18/01 and 9/24/02. No activity above background was detected.

Summary of PAS Results

- 149 filters in 142 days
- Cumulative exposure of
  - 32.2 DAC-hours with no PF applied
  - **31.3 DAC-hours with PF applied**
  - 16.8 DAC-hours with PF and DL applied


OPS-4   31.3 DAC-Hr (149 Filters in 142 Days)
DAC-HR (with PF)
2.5
2
1.5
1
0.5
0
-0.5
-1
0
50
100
150
200
250
300
350
400
DAY OF YEAR

OPS-5

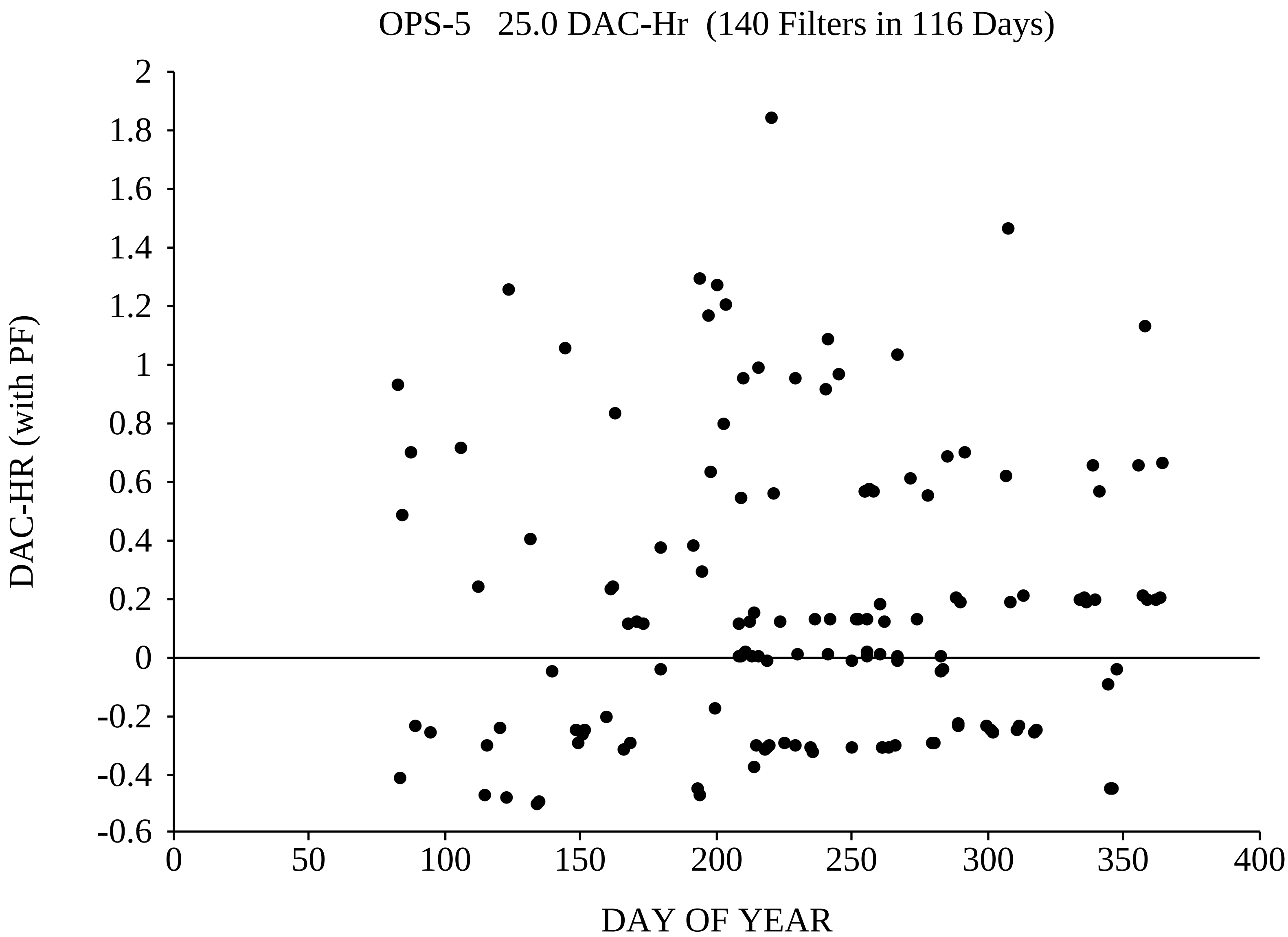
Bioassay Results

Work Date	Date	Time (days)	Nuclide	Sample Type	Result (pCi)	DL (pCi)	2σ error (pCi)
	10/2/2001	93	Am241	AS urine	0.001802	0.016667	0.009459
	10/2/2001	93	Pu238	AS urine	0.008108	0.020721	0.014865
	10/2/2001	93	Pu239	AS urine	-0.001802	0.018018	0.004054
9/14/01	9/17/2001	78	Am241	feces	0.000000	0.020270	0.009009
9/14/01	9/17/2001	78	Pu238	feces	0.010360	0.015315	0.014865
9/14/01	9/17/2001	78	Pu239	feces	0.010360	0.015315	0.014865
	9/16/2001	77	Pu239	MS urine	0.000059	0.000300	0.000035
	12/20/2001	172	Pu239	MS urine	-0.000002	0.000300	0.000052
	2/11/2002	**225**	**Pu239**	**MS urine**	**0.005990**	**0.000300**	**0.000501**
	5/12/2002	315	Pu239	MS urine	0.000045	0.000300	0.000061

Chest count on 10/2/01. No activity above background was detected.

Summary of PAS Results

- 140 filters in 116 days
- Cumulative exposure of
  29.5 DAC-hours with no PF applied
  25.0 DAC-hours with PF applied
  13.9 DAC-hours with PF and DL applied


OPS-5 25.0 DAC-Hr (140 Filters in 116 Days)
DAC-HR (with PF)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0
50
100
150
200
250
300
350
400
DAY OF YEAR

OPS-6

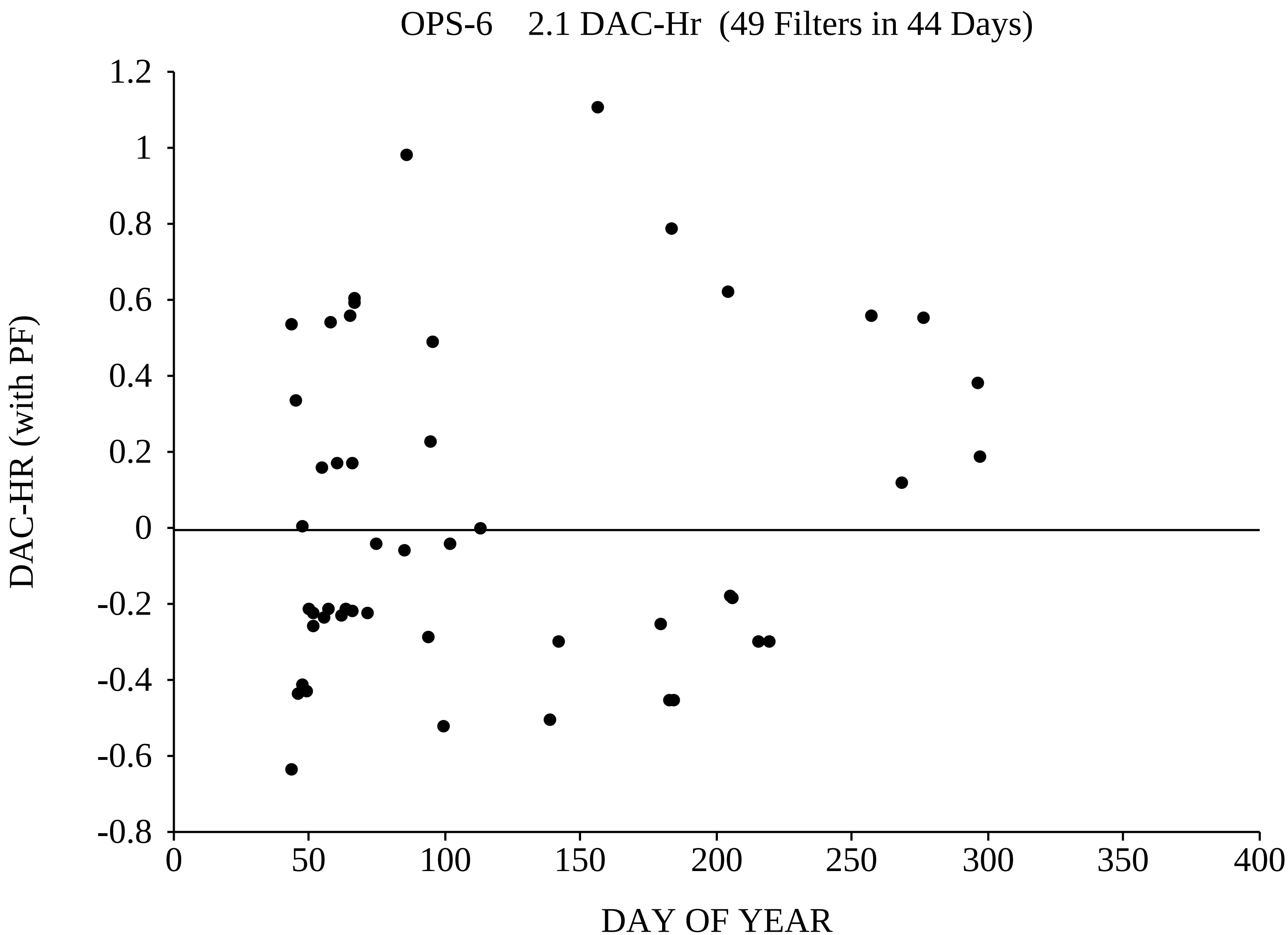
Bioassay Results

Work Date	Date	Time (days)	Nuclide	Sample Type	Result (pCi)	DL (pCi)	2σ error (pCi)
	4/17/2001	-75	Am241	AS urine	0.009113	0.011964	0.010734
	4/17/2001	-75	Pu238	AS urine	-0.002049	0.012883	0.007104
	4/17/2001	-75	Pu239	AS urine	0.006144	0.012883	0.010865
8/9/01	8/11/2001	41	Am241	feces	0.019653	0.020644	0.020032
8/9/01	8/11/2001	41	Pu238	feces	-0.003656	0.025676	0.016365
8/9/01	**8/11/2001**	**41**	**Pu239**	**feces**	**0.021923**	**0.019455**	**0.021027**
	4/25/2002	298	Pu238	AS urine	0.004505	0.013964	0.009009
	4/25/2002	298	Pu239	AS urine	0.005856	0.009009	0.008559
	8/10/2001	40	Pu239	MS urine	LIA		
	11/25/2001	**147**	**Pu239**	**MS urine**	**0.001580**	**0.000300**	**0.000101**
	2/21/2002	**235**	**Pu239**	**MS urine**	**0.000674**	**0.000300**	**0.000319**
	6/22/2002	**356**	**Pu239**	**MS urine**	**0.000920**	**0.000300**	**0.000051**

Chest count on 4/25/02. No activity above background was detected.

Summary of PAS Results

- 49 filters in 44 days
- Cumulative exposure of
  - 2.8 DAC-hours with no PF applied
  - **2.1 DAC-hours with PF applied**
  - 1.1 DAC-hours with PF and DL applied


OPS-6   2.1 DAC-Hr (49 Filters in 44 Days)
DAC-HR (with PF)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
0
50
100
150
200
250
300
350
400
DAY OF YEAR

OPS-7

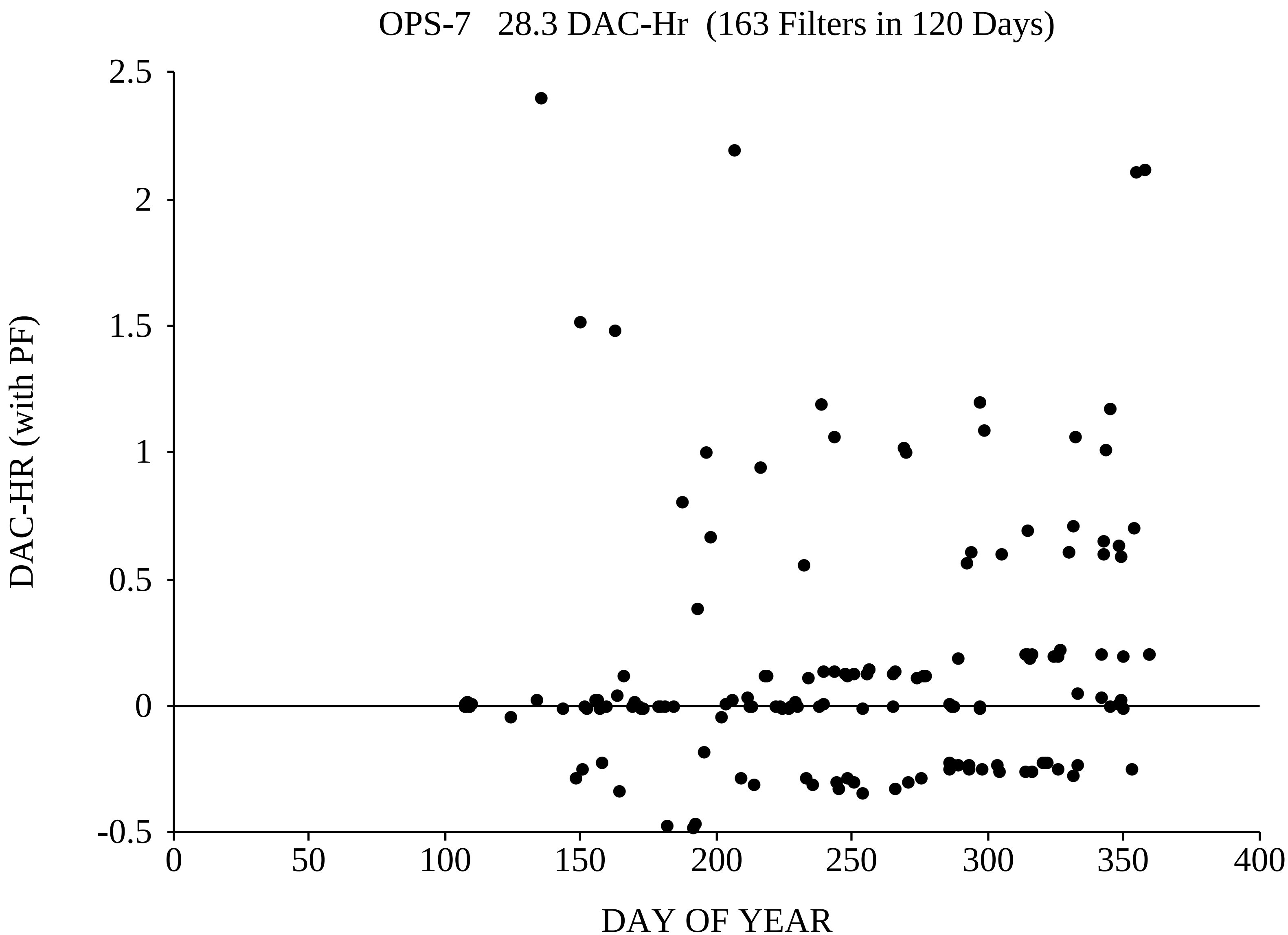
Bioassay Results

Work Date	Date	Time (days)	Nuclide	Sample Type	Result (pCi)	DL (pCi)	2σ error (pCi)
8/23/01	9/1/2001	62	Am241	feces	0.009459	0.016667	0.013964
8/23/01	9/1/2001	62	Pu238	feces	0.009910	0.029730	0.019820
8/23/01	9/1/2001	62	Pu239	feces	0.019820	0.029730	0.028378
	11/13/2001	135	Am241	AS urine	-0.001351	0.012613	0.002703
	11/13/2001	135	Pu238	AS urine	0.015315	0.020270	0.018468
	11/13/2001	135	Pu239	AS urine	0.002252	0.020270	0.009910
	11/21/2001	143	Am241	feces	0.007207	0.022072	0.014414
	11/21/2001	143	Pu238	feces	0.018018	0.023874	0.021622
	11/21/2001	143	Pu239	feces	0.000000	0.015315	0.000000
	11/21/2001	143	Am241	special	0.001351	0.007658	0.004505
	11/21/2001	143	Pu238	special	-0.000901	0.009009	0.001802
	11/21/2001	143	Pu239	special	0.000901	0.009009	0.004505
	9/1/2001	62	Pu239	MS urine	0.000015	0.000300	0.000035
	11/26/2001	148	Pu239	MS urine	0.000002	0.000300	0.000038
	3/20/2002	262	Pu239	MS urine	0.000023	0.000300	0.000081
	6/1/2002	335	Pu239	MS urine	0.000051	0.000300	0.000059

Chest counts on 11/13/01 and 11/20/01. The 11/20/01 chest counts was a 60-minute special in response to a high PAS result. No activity above background was detected.

Summary of PAS Results

- 163 filters in 120 days
- Cumulative exposure of
  169.8 DAC-hours with no PF applied
  28.3 DAC-hours with PF applied
  23.0 DAC-hours with PF and DL applied



OPS-7   28.3 DAC-Hr (163 Filters in 120 Days)
2.5
2
1.5
1
0.5
0
-0.5
0
50
100
150
200
250
300
350
400
DAC-HR (with PF)
DAY OF YEAR

OPS-8

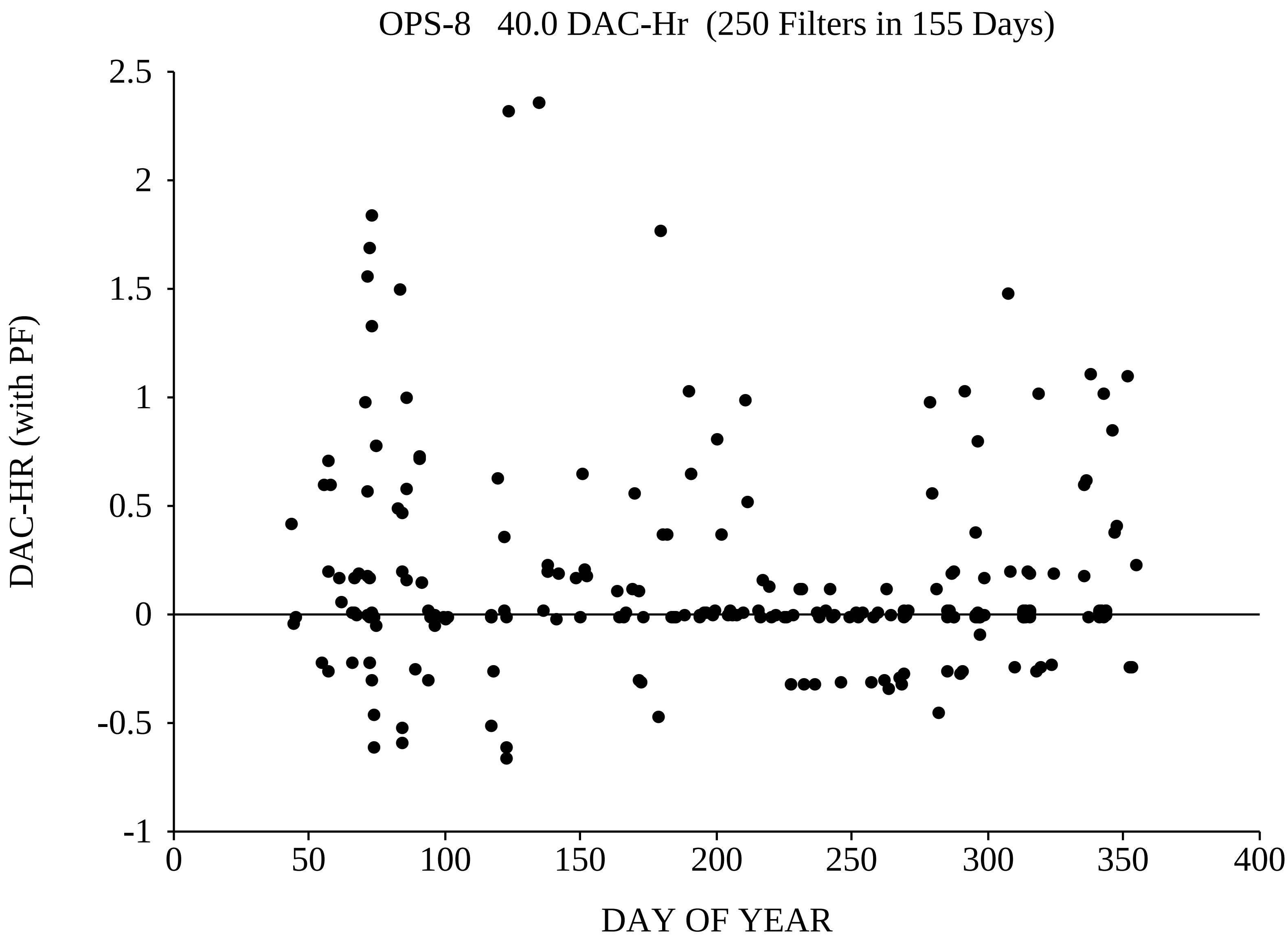
Bioassay Results

Work Date	Date	Time (days)	Nuclide	Sample Type	Result (pCi)	DL (pCi)	2σ error (pCi)
8/10/01	**8/12/2001**	**42**	**Am241**	**feces**	**0.014230**	**0.007113**	**0.011730**
8/10/01	8/12/2001	42	Pu238	feces	0.000000	0.030806	0.000000
8/10/01	8/12/2001	42	Pu239	feces	0.021923	0.030806	0.029387
	12/11/2001	163	Am241	AS urine	0.001351	0.010360	0.004955
	12/11/2001	163	Pu238	AS urine	0.009910	0.030180	0.019820
	12/11/2001	163	Pu239	AS urine	0.000000	0.019820	0.000000
	8/12/2001	42	Pu239	MS urine	LIA		
	12/5/2001	157	Pu239	MS urine	0.000049	0.000300	0.000036
	2/12/2002	226	Pu239	MS urine	LIA		
	6/5/2002	339	Pu239	MS urine	0.000064	0.000300	0.000036

Chest count on 12/11/01. No activity above background was detected.

Summary of PAS Results

- 250 filters in 155 days
- Cumulative exposure of
  84.8 DAC-hours with no PF applied
  40.0 DAC-hours with PF applied
  26.3 DAC-hours with PF and DL applied


OPS-8   40.0 DAC-Hr (250 Filters in 155 Days)
DAC-HR (with PF)
2.5
2
1.5
1
0.5
0
-0.5
-1
0
50
100
150
200
250
300
350
400
DAY OF YEAR

OPS-9

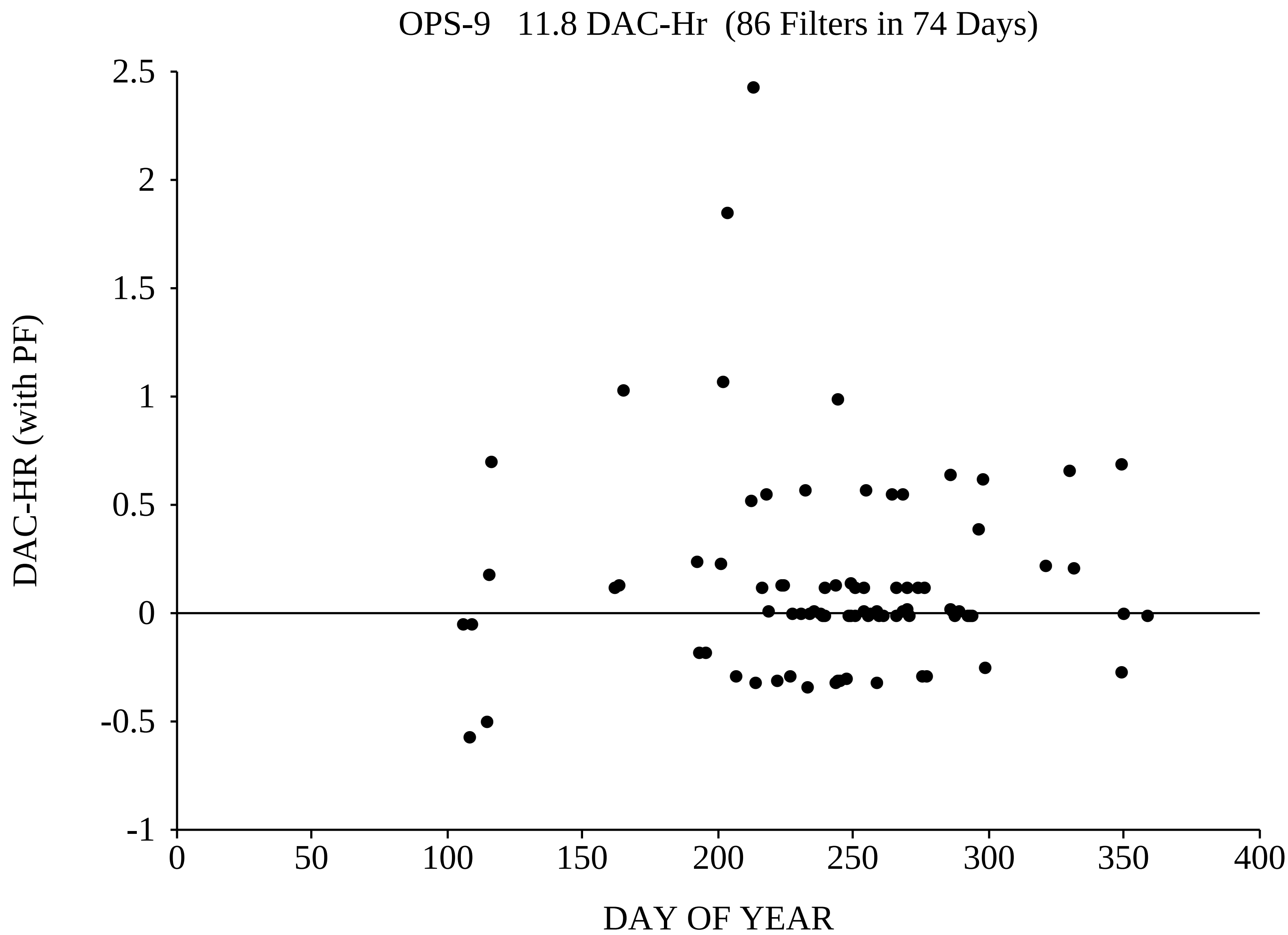
Bioassay Results

Work Date	Date	Time (days)	Nuclide	Sample Type	Result (pCi)	DL (pCi)	2σ error (pCi)
	3/6/2001	-117	Pu238	AS urine	0.000000	0.007820	0.000000
	3/6/2001	-117	Pu239	AS urine	0.000000	0.007820	0.000000
	3/6/2001	-117	Pu239	AS urine	0.005009	0.007509	0.007113
8/30/01	9/4/2001	65	Am241	feces	0.009459	0.013964	0.013514
8/30/01	9/4/2001	65	Pu238	feces	0.014414	0.021622	0.020721
8/30/01	9/4/2001	65	Pu239	feces	0.014414	0.021622	0.020721
	2/28/2002	242	Am241	AS urine	0.006757	0.009910	0.009459
	2/28/2002	242	Pu238	AS urine	0.007658	0.020270	0.014414
	2/28/2002	242	Pu239	AS urine	0.001802	0.018018	0.008559
	9/3/2001	64	Pu239	MS urine	-0.000060	0.000300	0.000056
	12/1/2001	153	Pu239	MS urine	-0.000002	0.000300	0.000144
	2/24/2002	**238**	**Pu239**	**MS urine**	**0.000405**	**0.000300**	**0.000214**
	6/10/2002	344	Pu239	MS urine	0.000103	0.000300	0.000043

Chest count on 2/28/02. No activity above background was detected.

Summary of PAS Results

- 86 filters in 74 days
- Cumulative exposure of
  24.6 DAC-hours with no PF applied
  11.8 DAC-hours with PF applied
  6.6 DAC-hours with PF and DL applied



OPS-9 11.8 DAC-Hr (86 Filters in 74 Days)
DAC-HR (with PF)
2.5
2
1.5
1
0.5
0
-0.5
-1
0
50
100
150
200
250
300
350
400
DAY OF YEAR

OPS-10

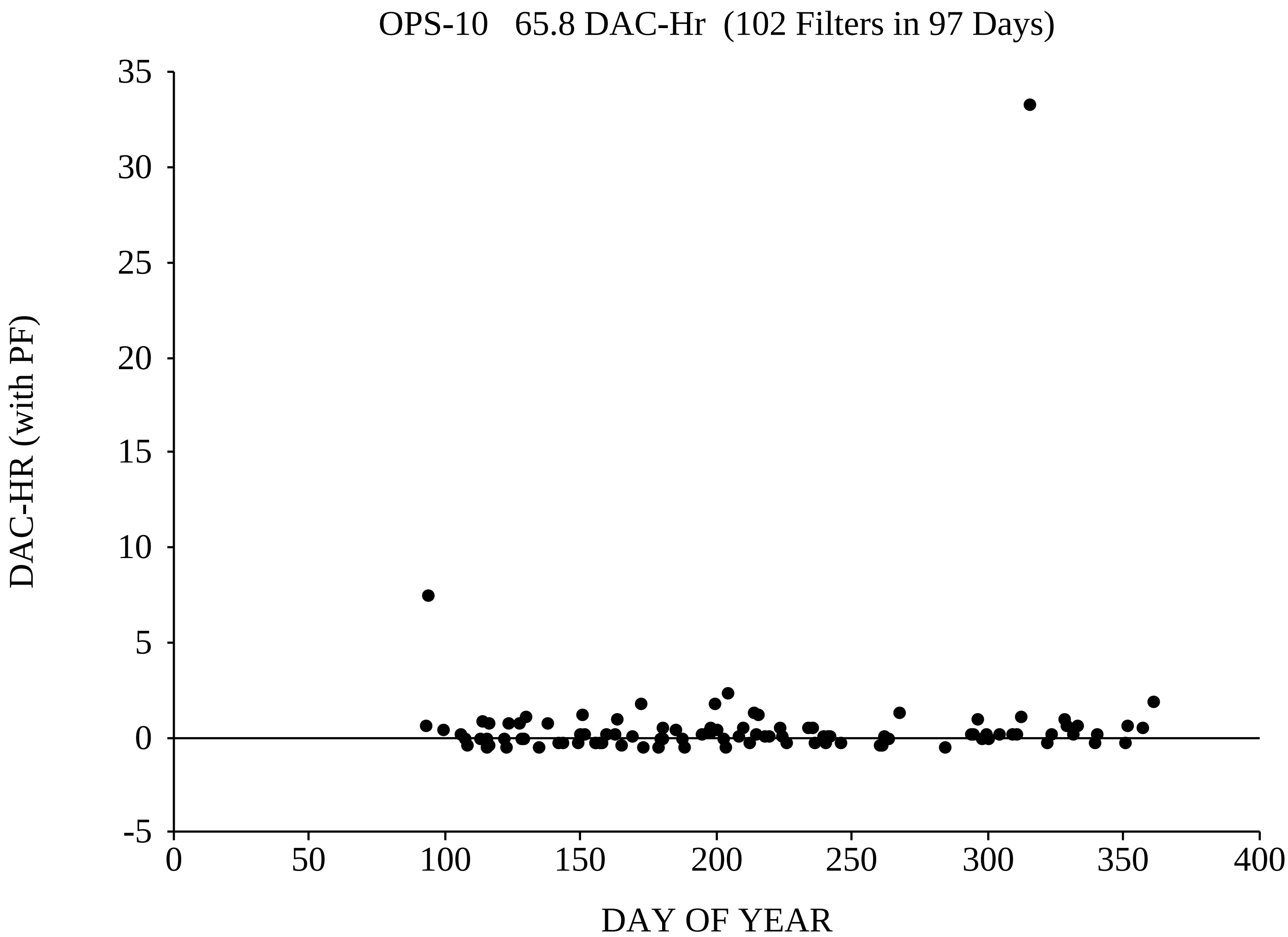
Bioassay Results

Work Date	Date	Time (days)	Nuclide	Sample Type	Result (pCi)	DL (pCi)	2σ error (pCi)
	1/17/2001	-165	Pu238	AS urine	-0.005176	0.028275	0.007369
	1/18/2001	-164	Pu239	AS urine	-0.007761	0.031023	0.009045
	1/22/2001	-160	Am241	AS urine	0.002900	0.014856	0.008838
9/20/01	9/24/2001	85	Am241	feces	0.008108	0.021622	0.015315
9/20/01	9/24/2001	85	Pu238	feces	0.011261	0.028829	0.020270
9/20/01	9/24/2001	85	Pu239	feces	0.002703	0.025225	0.012162
	10/4/2001	**95**	**Am241**	**feces**	**0.990541**	**0.017568**	**0.147297**
	10/4/2001	**95**	**Pu238**	**feces**	**0.504505**	**0.016216**	**0.150000**
	10/4/2001	**95**	**Pu239**	**feces**	**11.004505**	**0.029279**	**2.377477**
	10/4/2001	**95**	**Am241**	**special**	**0.006306**	**0.004505**	**0.005405**
	10/4/2001	95	Pu238	special	0.002252	0.007207	0.004505
	10/4/2001	95	Pu239	special	0.003604	0.007207	0.005405
	1/17/2002	200	Am241	AS urine	0.005405	0.016667	0.010811
	1/17/2002	200	Pu238	AS urine	0.000000	0.022072	0.009910
	1/17/2002	200	Pu239	AS urine	-0.008108	0.026126	0.008108
	5/17/2002	**320**	**Am241**	**feces**	**0.026126**	**0.015766**	**0.019820**
	5/17/2002	**320**	**Pu238**	**feces**	**0.032883**	**0.019369**	**0.024775**
	5/17/2002	**320**	**Pu239**	**feces**	**0.423423**	**0.010811**	**0.101351**
	5/17/2002	320	Am241	special	0.001351	0.013063	0.006306
	5/17/2002	320	Pu238	special	0.001802	0.014414	0.006757
	5/17/2002	320	Pu239	special	0.003153	0.009459	0.006306
	9/23/2001	84	Pu239	MS urine	0.000067	0.000300	0.000056
	11/29/2001	151	Pu239	MS urine	0.000286	0.000300	0.000112
	2/18/2002	232	Pu239	MS urine	0.000272	0.000300	0.000138
	5/29/2002	332	Pu239	MS urine	0.000200	0.000300	0.000043

Chest counts on 10/3/01 and 1/17/02. No activity above background was detected.

Summary of PAS Results

- 102 filters in 97 days
- Cumulative exposure of
  65.6 DAC-hours with no PF applied
  65.8 DAC-hours with PF applied
  59.2 DAC-hours with PF and DL applied



OPS-10   65.8 DAC-Hr (102 Filters in 97 Days)
DAC-HR (with PF)
35
30
25
20
15
10
5
0
-5
0
50
100
150
200
250
300
350
400
DAY OF YEAR

OPS-11

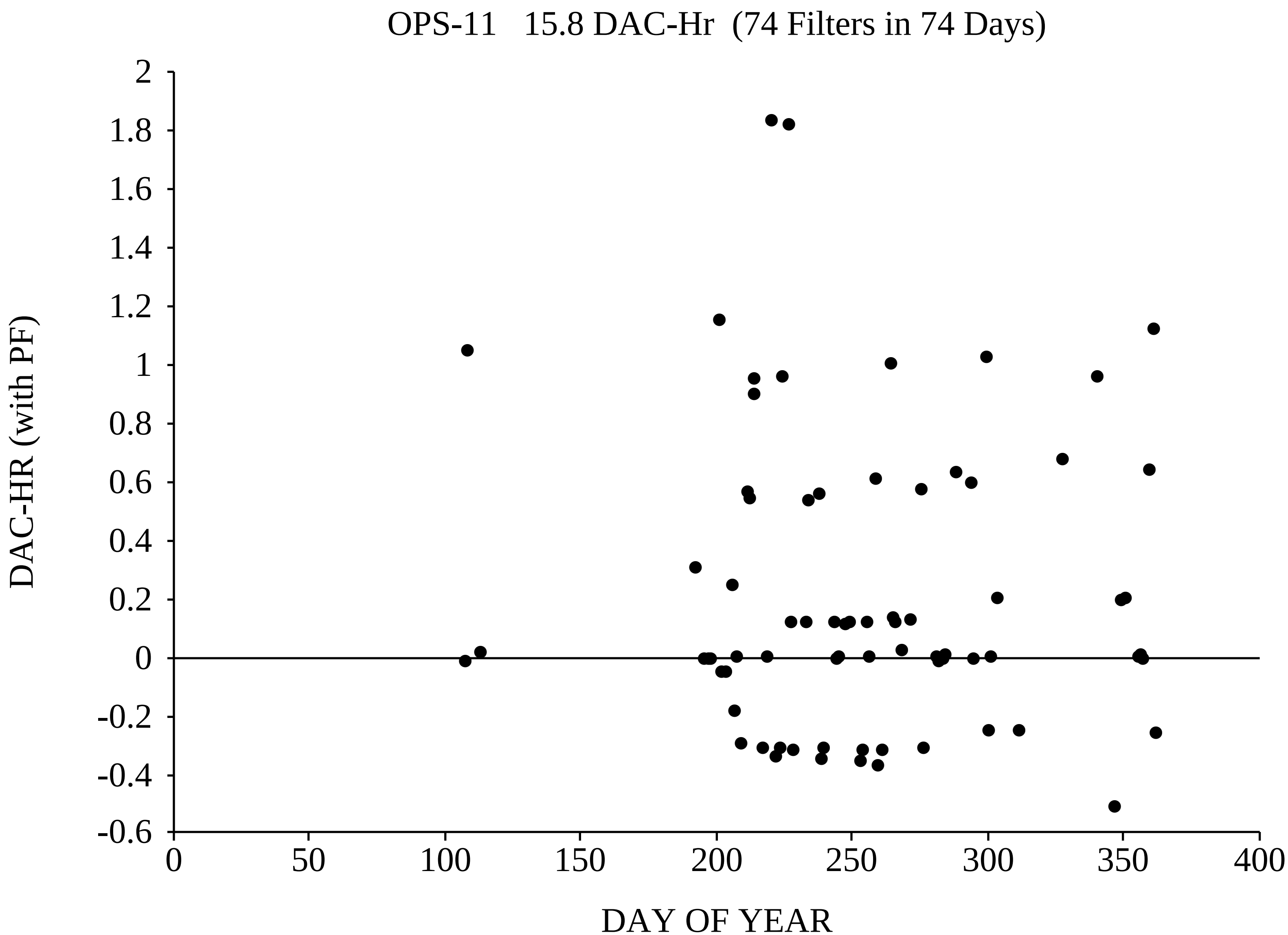
Bioassay Results

Work Date	Date	Time (days)	Nuclide	Sample Type	Result (pCi)	DL (pCi)	2σ error (pCi)
	7/3/2001	**2**	**Am241**	**AS urine**	**0.007928**	**0.003963**	**0.006541**
	7/3/2001	2	Pu238	AS urine	0.002482	0.006604	0.004968
	7/3/2001	2	Pu239	AS urine	0.001240	0.003721	0.002484
8/16/01	8/19/2001	49	Am241	feces	0.007077	0.009423	0.008703
8/16/01	8/19/2001	49	Pu238	feces	0.016450	0.021887	0.020378
8/16/01	8/19/2001	49	Pu239	feces	-0.004110	0.021887	0.008257
	8/20/2001	50	Am241	special	0.000620	0.003302	0.002149
	6/6/2002	340	Am241	AS urine	0.003153	0.009459	0.006306
	6/6/2002	340	Pu238	AS urine	0.000000	0.014414	0.006757
	6/6/2002	340	Pu239	AS urine	0.001351	0.012613	0.005856
	8/19/2001	49	Pu239	MS urine	0.000000	0.000300	0.000035
	12/16/2001	168	Pu239	MS urine	-0.000056	0.000300	0.000077
	2/25/2002	239	Pu239	MS urine	0.000111	0.000300	0.000069
	6/14/2002	348	Pu239	MS urine	0.000045	0.000300	0.000015

Chest counts on 6/28/01 and 6/6/02. No activity above background was detected.

Summary of PAS Results

- 74 filters in 74 days
- Cumulative exposure of
  - 18.9 DAC-hours with no PF applied
  - **15.8 DAC-hours with PF applied**
  - 9.1 DAC-hours with PF and DL applied


OPS-11 15.8 DAC-Hr (74 Filters in 74 Days)
DAC-HR (with PF)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0
50
100
150
200
250
300
350
400
DAY OF YEAR

OPS-12

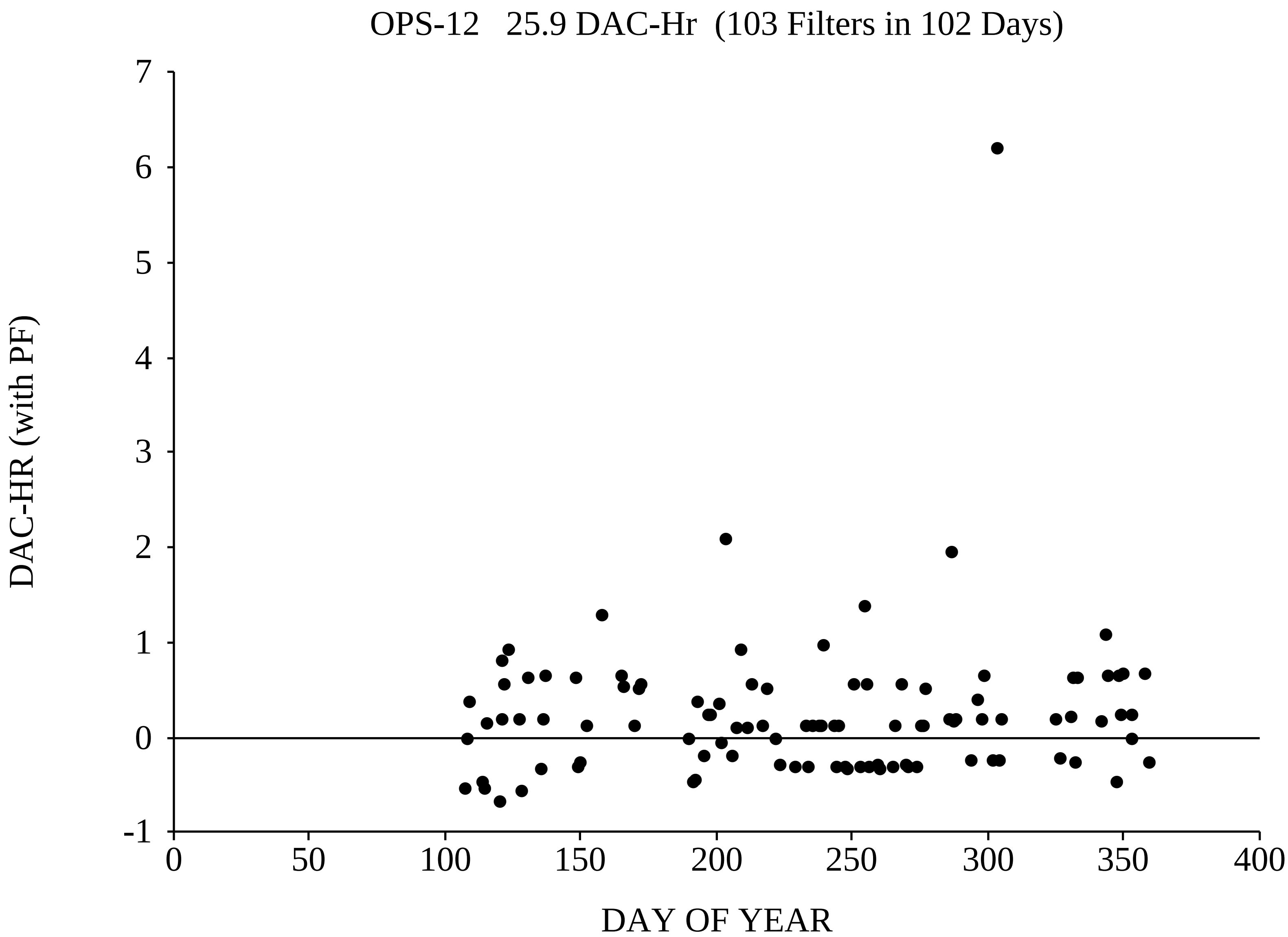
Bioassay Results

Work Date	Date	Time (days)	Nuclide	Sample Type	Result (pCi)	DL (pCi)	2σ error (pCi)
8/16/01	8/19/2001	49	Am241	feces	0.003379	0.008995	0.006766
8/16/01	8/19/2001	49	Pu238	feces	0.012428	0.026027	0.022036
8/16/01	8/19/2001	49	Pu239	feces	-0.004139	0.026027	0.014360
	8/21/2001	51	Am241	AS urine	0.001351	0.006306	0.004054
	8/21/2001	51	Pu238	AS urine	0.003153	0.009910	0.006757
	8/21/2001	51	Pu239	AS urine	0.000000	0.009910	0.000000
	12/11/2001	**163**	**Am241**	**special**	**0.007658**	**0.004054**	**0.006306**
	12/11/2001	163	Pu238	special	0.002252	0.006757	0.004505
	12/11/2001	163	Pu239	special	-0.000901	0.010360	0.002252
	7/24/2002	388	Am241	AS urine	0.002703	0.007658	0.005405
	7/24/2002	388	Pu238	AS urine	0.000000	0.013514	0.006306
	7/24/2002	388	Pu239	AS urine	0.001351	0.011712	0.005856
	8/19/2001	49	Pu239	MS urine	-0.000017	0.000300	0.000082
	12/19/2001	171	Pu239	MS urine	-0.000005	0.000300	0.000123
	3/1/2002	**243**	**Pu239**	**MS urine**	**0.000374**	**0.000300**	**0.000088**
	5/30/2002	333	Pu239	MS urine	0.000119	0.000300	0.000019

Chest counts on 8/20/01 and 8/22/02. No activity above background was detected.

Summary of PAS Results

- 103 filters in 102 days
- Cumulative exposure of
  26.0 DAC-hours with no PF applied
  25.9 DAC-hours with PF applied
  14.1 DAC-hours with PF and DL applied


OPS-12 25.9 DAC-Hr (103 Filters in 102 Days)
DAC-HR (with PF)
7
6
5
4
3
2
1
0
-1
0
50
100
150
200
250
300
350
400
DAY OF YEAR

OPS-13

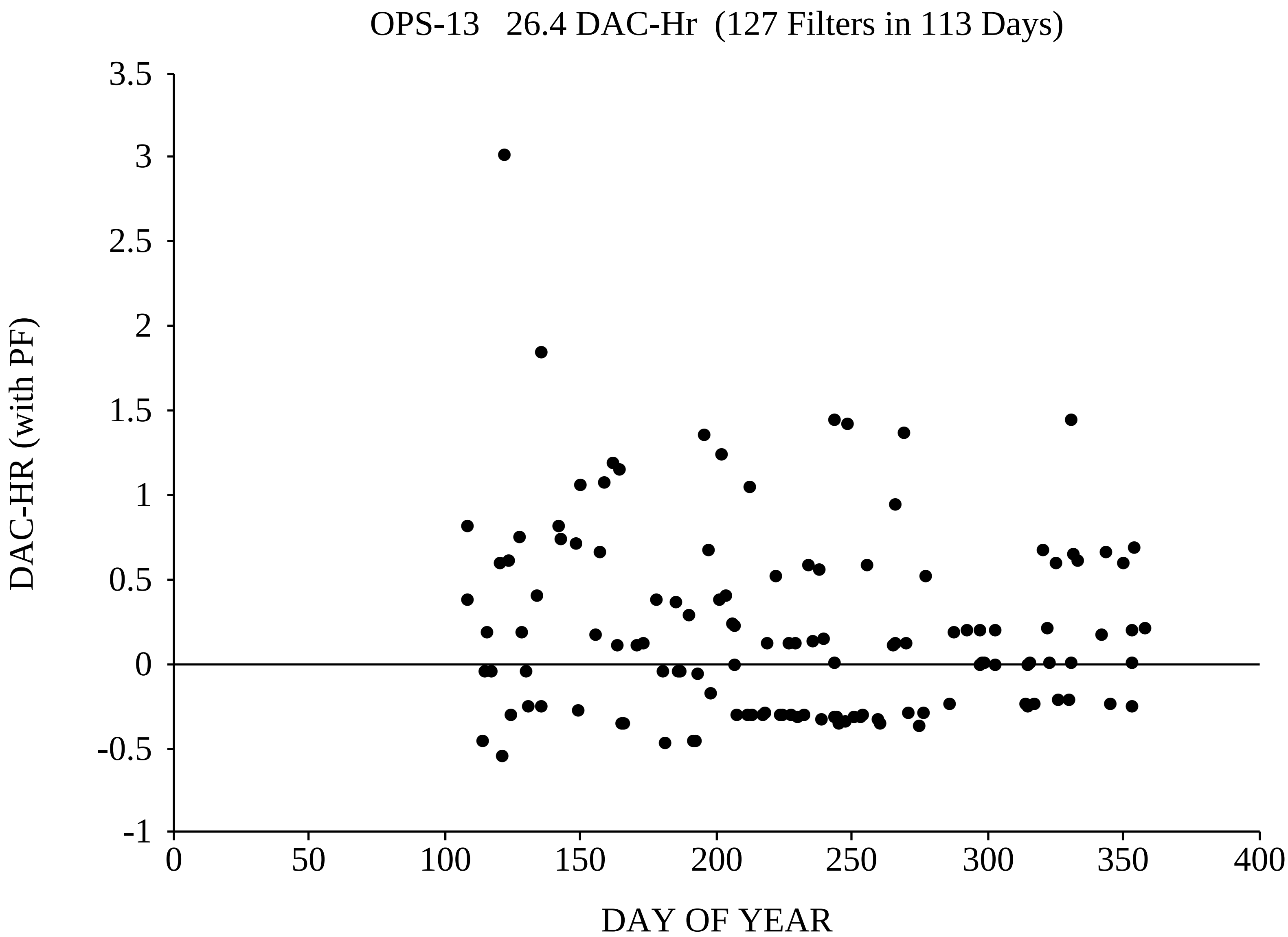
Bioassay Results

Work Date	Date	Time (days)	Nuclide	Sample Type	Result (pCi)	DL (pCi)	2σ error (pCi)
8/23/01	8/30/2001	60	Am241	feces	0.000000	0.017117	0.010811
8/23/01	8/30/2001	60	Pu238	feces	0.013514	0.020270	0.019369
8/23/01	8/30/2001	60	Pu239	feces	0.006757	0.020270	0.013514
	9/19/2001	80	Pu238	AS urine	0.000000	0.010360	0.000000
	9/19/2001	80	Pu239	AS urine	0.000000	0.018468	0.008559
	8/30/2001	60	Pu239	MS urine	0.000008	0.000300	0.000050
	12/8/2001	160	Pu239	MS urine	0.000056	0.000300	0.000053
	3/1/2002	243	Pu239	MS urine	0.000127	0.000300	0.000123
	6/2/2002	336	Pu239	MS urine	0.000194	0.000300	0.000047

Chest counts on 9//19/01 and 9/17/02. No activity above background was detected.

Summary of PAS Results

- 127 filters in 113 days
- Cumulative exposure of
  27.8 DAC-hours with no PF applied
  26.4 DAC-hours with PF applied
  18.7 DAC-hours with PF and DL applied


OPS-13 26.4 DAC-Hr (127 Filters in 113 Days)
DAC-HR (with PF)
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
0
50
100
150
200
250
300
350
400
DAY OF YEAR

RPD-1

Bioassay Results

Work Date	Date	Time (days)	Nuclide	Sample Type	Result (pCi)	DL (pCi)	2σ error (pCi)
	4/2/2001	-90	Am241	AS urine	0.005968	0.008950	0.008477
	4/2/2001	-90	Pu238	AS urine	-0.001295	0.012360	0.002596
	4/2/2001	-90	Pu239	AS urine	0.002677	0.008032	0.005365
7/5/01	7/9/2001	8	Am241	feces	0.000000	0.013387	0.000000
7/5/01	7/9/2001	8	Pu238	feces	-0.002247	0.021432	0.004514
7/5/01	7/9/2001	8	Pu239	feces	0.009284	0.013923	0.013252
11/28/01	11/29/2001	151	Am241	feces	0.000000	0.031081	0.013964
11/28/01	11/29/2001	151	Pu238	feces	-0.005405	0.028829	0.010811
11/28/01	11/29/2001	151	Pu239	feces	0.021622	0.028829	0.027027
2/11/02	2/12/2002	226	Am241	feces	-0.004955	0.019369	0.005856
2/11/02	2/12/2002	226	Pu238	feces	0.009910	0.029279	0.019820
2/11/02	2/12/2002	226	Pu239	feces	0.019369	0.029279	0.027928
	3/7/2002	249	Pu238	AS urine	0.004054	0.012613	0.008108
	3/7/2002	249	Pu239	AS urine	0.001351	0.012613	0.006306
5/24/02	5/29/2002	332	Am241	feces	0.004505	0.007658	0.006306
5/24/02	5/29/2002	332	Pu238	feces	0.007207	0.021171	0.013964
5/24/02	5/29/2002	332	Pu239	feces	0.011712	0.021171	0.016667
	7/8/2001	7	Pu239	MS urine	0.000095	0.000300	0.000166
	11/25/2001	147	Pu239	MS urine	-0.000027	0.000300	0.000066
	2/10/2002	224	Pu239	MS urine	0.000129	0.000300	0.000098
	5/28/2002	331	Pu239	MS urine	-0.000018	0.000300	0.000040

Chest count on 3/7/02. No activity above background was detected.

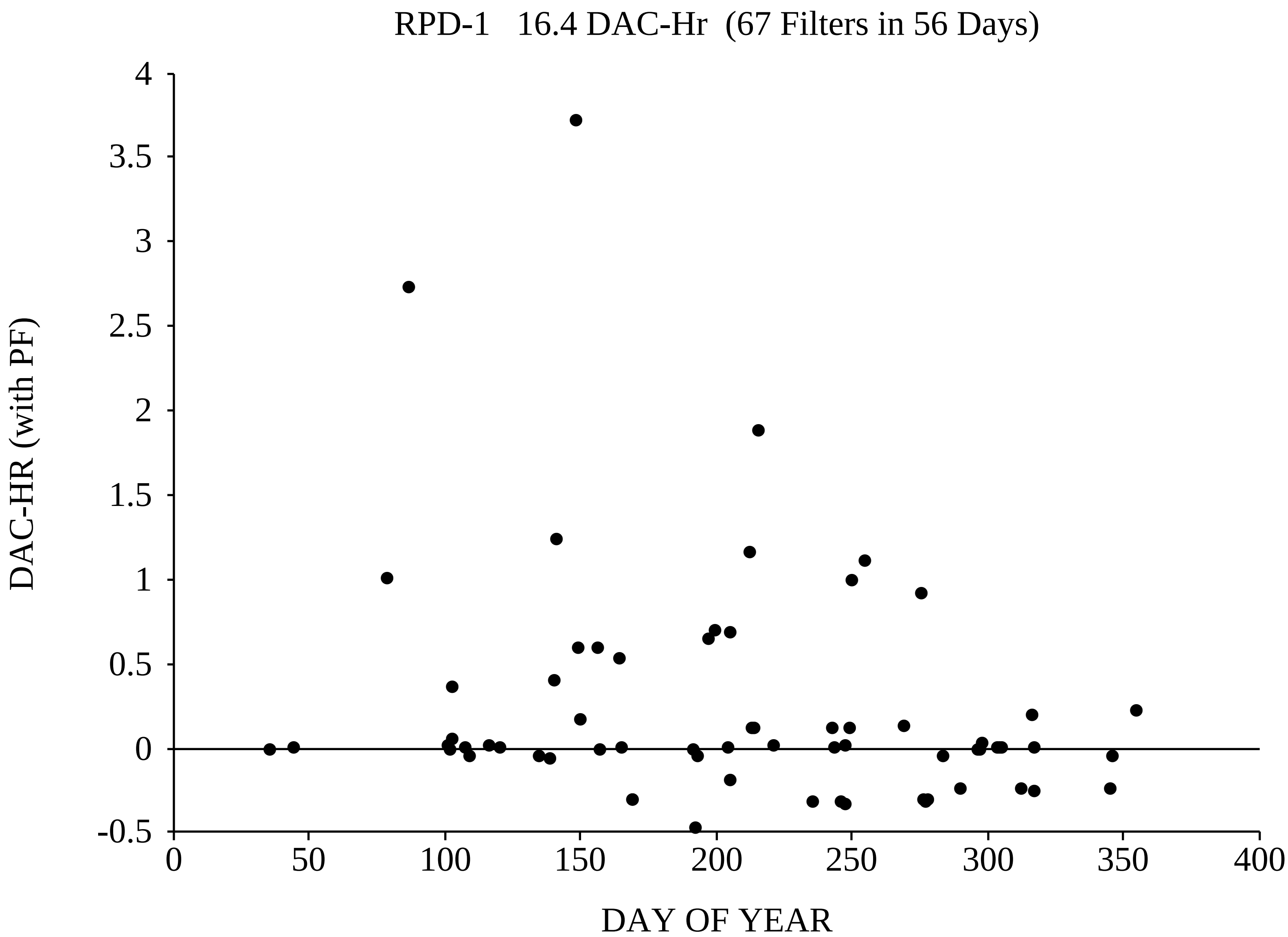
Summary of PAS Results

- 67 filters in 56 days
- Cumulative exposure of

  26.1 DAC-hours with no PF applied

  16.4 DAC-hours with PF applied

  13.0 DAC-hours with PF and DL applied


RPD-1 16.4 DAC-Hr (67 Filters in 56 Days)
DAC-HR (with PF)
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
0
50
100
150
200
250
300
350
400
DAY OF YEAR

RPD-2

Bioassay Results

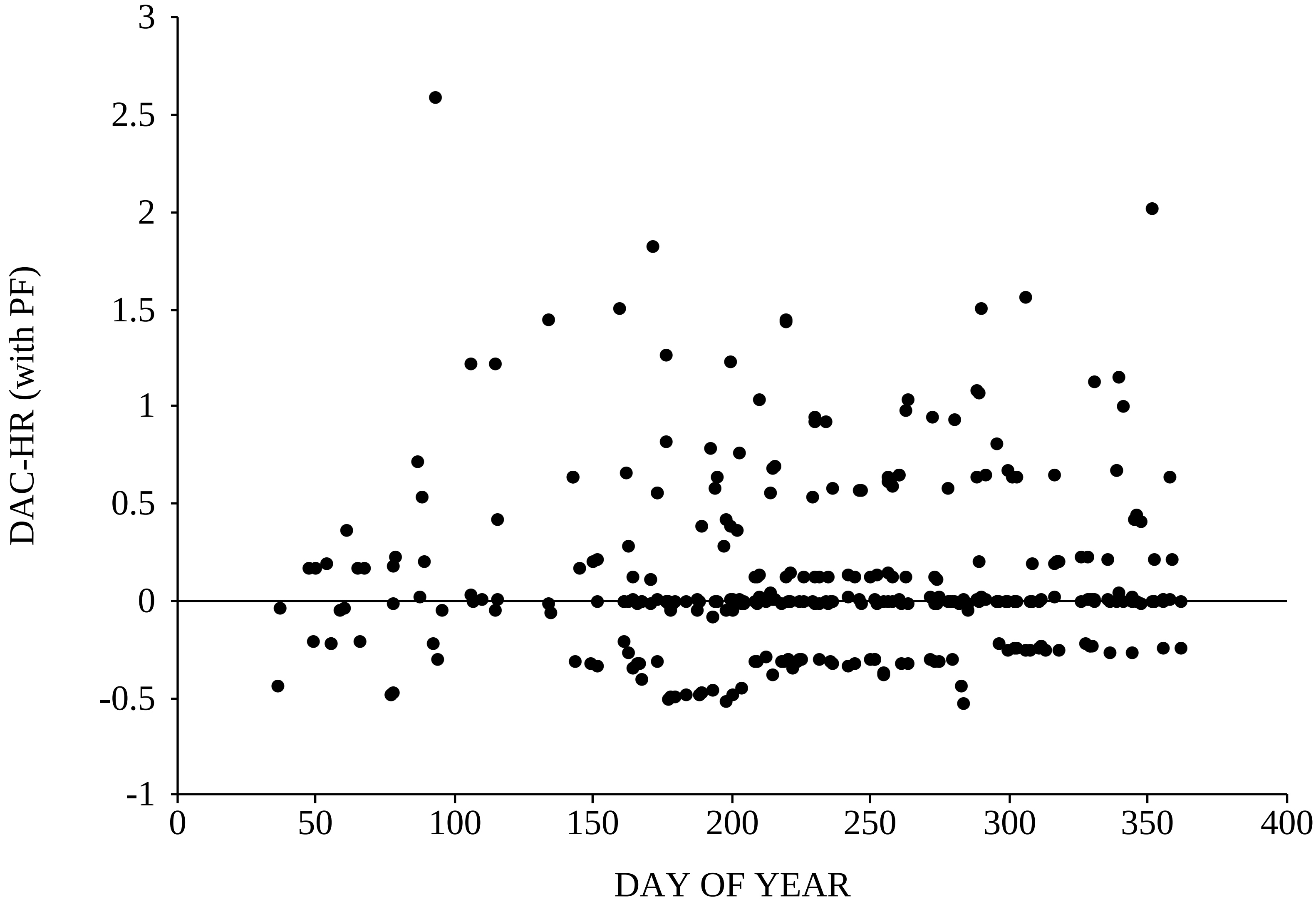
Work Date	Date	Time (days)	Nuclide	Sample Type	Result (pCi)	DL (pCi)	2σ error (pCi)
	1/29/2001	-153	Am241	AS urine	0.011293	0.011545	0.011536
	1/29/2001	-153	Pu238	AS urine	0.005486	0.008225	0.007793
	1/29/2001	-153	Pu239	AS urine	0.009644	0.012662	0.011351
8/2/01	8/6/2001	36	Am241	feces	0.009662	0.014495	0.013734
8/2/01	8/6/2001	36	Pu238	feces	0.008707	0.013054	0.012423
8/2/01	8/6/2001	36	Pu239	feces	-0.008423	0.027126	0.008572
12/1/01	12/7/2001	159	Am241	feces	0.007658	0.023423	0.015315
12/1/01	12/7/2001	159	Pu238	feces	0.006306	0.018919	0.012613
12/1/01	12/7/2001	159	Pu239	feces	0.006306	0.018919	0.012613
	1/15/2002	198	Am241	AS urine	0.004054	0.020721	0.012162
	1/15/2002	198	Pu238	AS urine	0.024324	0.024775	0.025225
	1/15/2002	198	Pu239	AS urine	0.002703	0.024775	0.012162
3/13/02	3/14/2002	256	Am241	feces	-0.003153	0.017568	0.004505
3/13/02	3/14/2002	256	Pu238	feces	0.000000	0.014865	0.000000
3/13/02	3/14/2002	256	Pu239	feces	0.009910	0.014865	0.013964
5/28/02	5/30/2002	-32	Am241	feces	0.009009	0.013514	0.013063
5/28/02	5/30/2002	-32	Pu238	feces	-0.003153	0.019369	0.010811
5/28/02	5/30/2002	-32	Pu239	feces	0.009459	0.009459	0.010811
	8/6/2001	36	Pu239	MS urine	-0.000068	0.000300	0.001230
	12/10/2001	162	Pu239	MS urine	LIA		
	3/14/2002	256	Pu239	MS urine	-0.000041	0.000300	0.000092
	5/29/2002	332	Pu239	MS urine	0.000050	0.000300	0.000053

Chest counts on 1/23/01 and 1/15/02. No activity above background was detected.

Summary of PAS Results

- 328 filters in 151 days
- Cumulative exposure of
  - 62.1 DAC-hours with no PF applied
  - **41.1 DAC-hours with PF applied**
  - 28.1 DAC-hours with PF and DL applied

RPD-2 41.1 DAC-Hr (328 Filters in 151 Days)



RPD-3

Bioassay Results

Work Date	Date	Time (days)	Nuclide	Sample Type	Result (pCi)	DL (pCi)	2σ error (pCi)
7/5/01	7/9/2001	8	Am241	feces	0.006477	0.019432	0.012995
7/5/01	7/9/2001	8	Pu238	feces	0.011959	0.017937	0.017113
7/5/01	7/9/2001	8	Pu239	feces	0.009063	0.027604	0.017977
	8/31/2001	61	Am241	AS urine	-0.001351	0.014414	0.003153
	8/31/2001	61	Pu238	AS urine	0.002252	0.020270	0.009459
	8/31/2001	61	Pu239	AS urine	0.002252	0.020270	0.009459
12/6/01	12/9/2001	161	Am241	feces	0.000000	0.012613	0.000000
12/6/01	12/9/2001	161	Pu238	feces	0.000000	0.027477	0.000000
12/6/01	12/9/2001	161	Pu239	feces	0.005405	0.015766	0.010360
2/25/02	2/26/2002	240	Am241	feces	0.011712	0.019369	0.016216
2/25/02	2/26/2002	240	Pu238	feces	0.000000	0.025225	0.011712
2/25/02	2/26/2002	240	Pu239	feces	-0.002252	0.027477	0.012613
7/2/02	7/7/2002	371	Am241	feces	0.006757	0.015315	0.013063
7/3/02	7/7/2002	371	Pu238	feces	0.008108	0.024324	0.016216
7/3/02	**7/7/2002**	**371**	**Pu239**	**feces**	**0.065315**	**0.024324**	**0.048198**
	7/8/2001	7	Pu239	MS urine	0.000031	0.000300	0.000347
	12/11/2001	163	Pu239	MS urine	0.000205	0.000300	0.000075
	2/25/2002	239	Pu239	MS urine	-0.000083	0.000300	0.000210
	7/17/2002	381	Pu239	MS urine	0.000028	0.000300	0.000026

Chest counts on 8/30/01 and 8/20/02. No activity above background was detected.

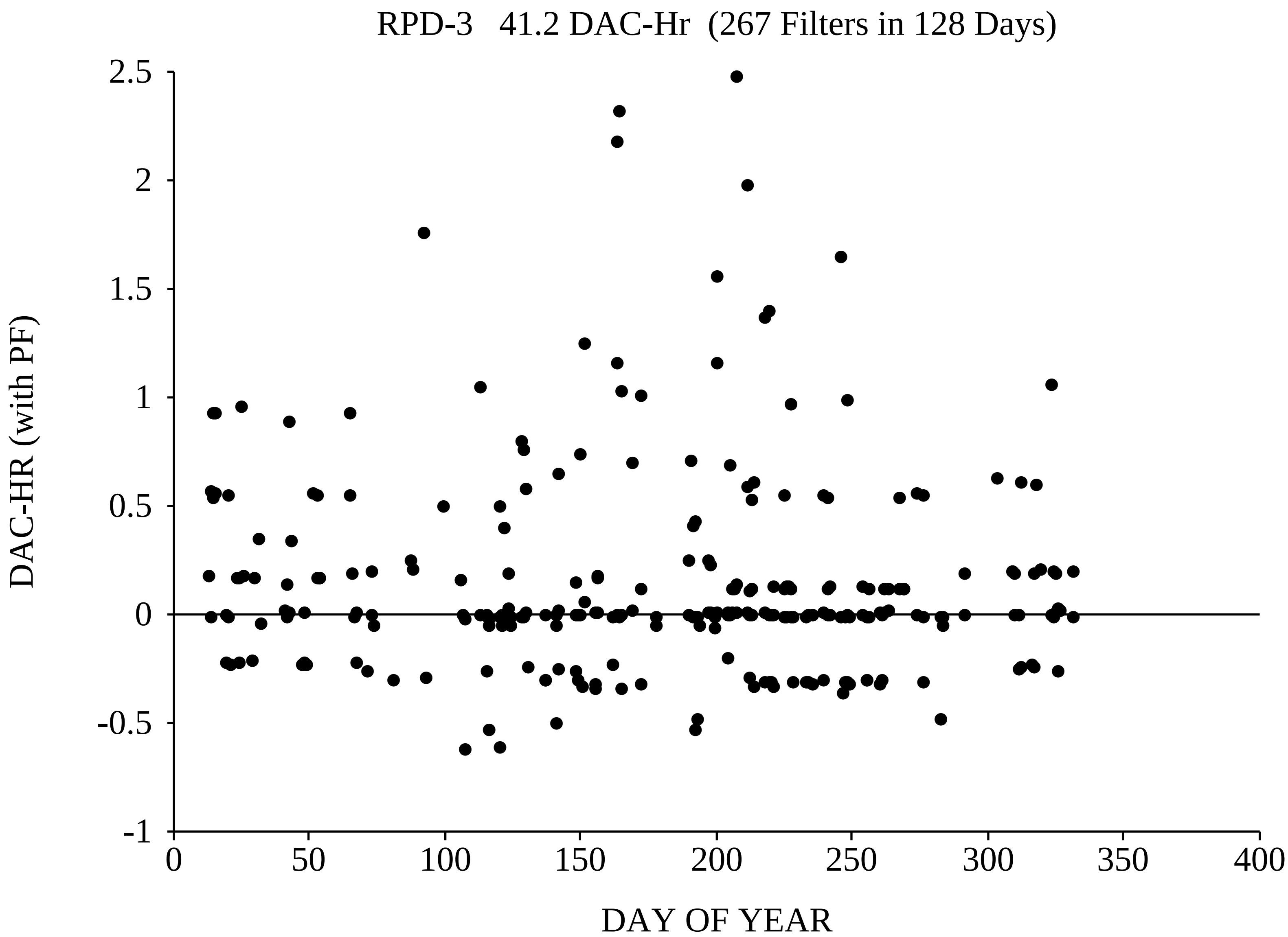
Summary of PAS Results

- 267 filters in 128 days
- Cumulative exposure of

  62.5 DAC-hours with no PF applied

  41.2 DAC-hours with PF applied

  24.8 DAC-hours with PF and DL applied


RPD-3 41.2 DAC-Hr (267 Filters in 128 Days)
DAC-HR (with PF)
DAY OF YEAR
2.5
2
1.5
1
0.5
0
-0.5
-1
0
50
100
150
200
250
300
350
400

RPD-4

Bioassay Results

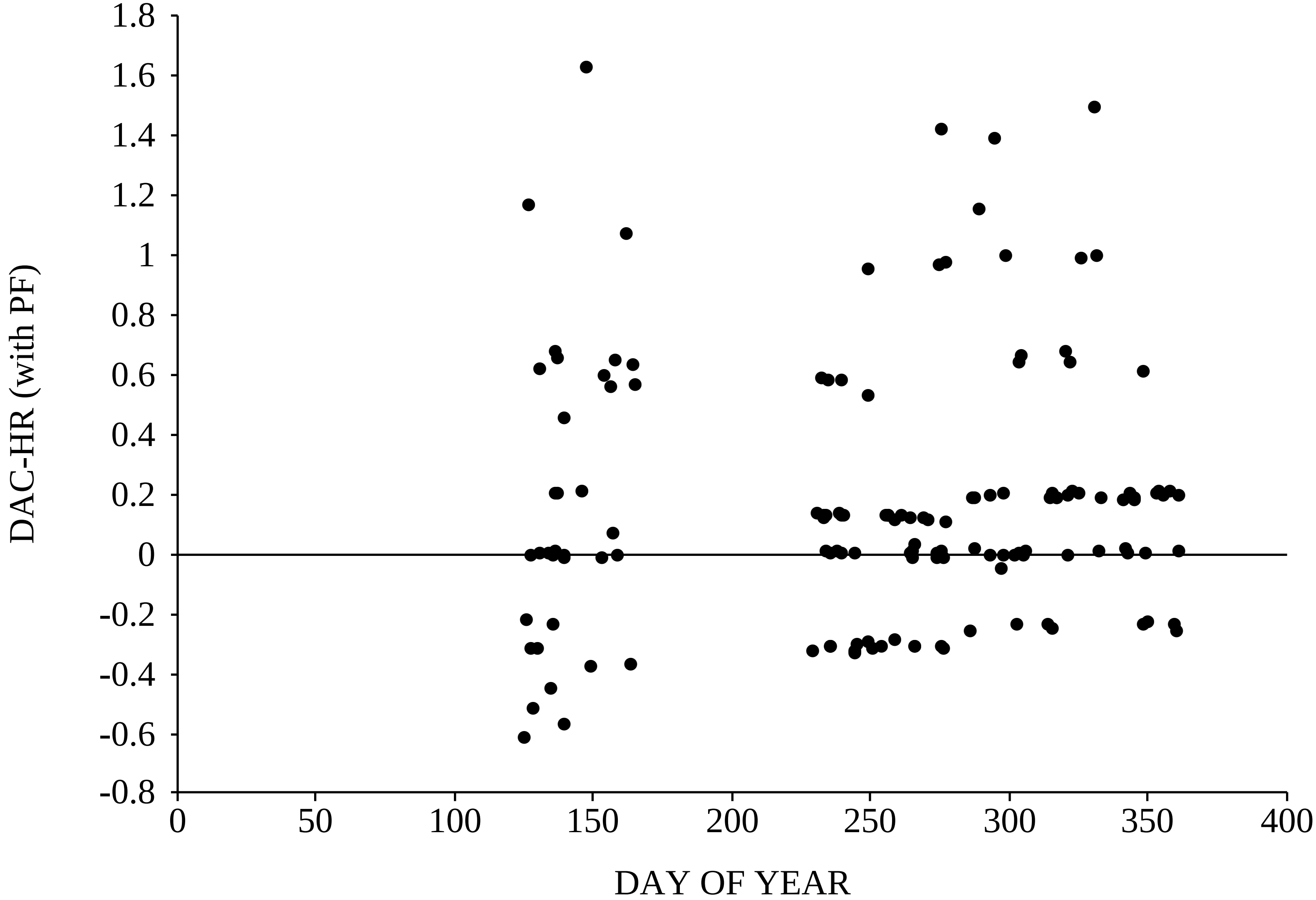
Work Date	Date	Time (days)	Nuclide	Sample Type	Result (pCi)	DL (pCi)	2σ error (pCi)
10/29/01	**10/29/2001**	**120**	**Am241**	**feces**	**0.016667**	**0.014865**	**0.015766**
10/29/01	10/29/2001	120	Pu238	feces	0.002252	0.020721	0.009910
10/29/01	10/29/2001	120	Pu239	feces	0.009009	0.023423	0.016667
	11/14/2001	136	Am241	AS urine	-0.001351	0.013514	0.002703
	11/14/2001	136	Pu238	AS urine	0.000000	0.021171	0.011712
	11/14/2001	136	Pu239	AS urine	0.003604	0.010360	0.006757
11/26/01	11/26/2001	148	Am241	feces	0.008108	0.015315	0.011712
11/26/01	11/26/2001	148	Pu238	feces	0.003153	0.009910	0.006757
11/26/01	11/26/2001	148	Pu239	feces	0.003153	0.022973	0.017568
3/7/02	**3/13/2002**	**255**	**Am241**	**feces**	**0.081081**	**0.009910**	**0.025225**
3/7/02	3/13/2002	255	Pu238	feces	0.015766	0.030180	0.027477
3/7/02	**3/13/2002**	**255**	**Pu239**	**feces**	**0.244595**	**0.021171**	**0.073874**
5/12/02	5/12/2002	315	Am241	feces	0.002703	0.013063	0.008559
5/12/02	5/12/2002	315	Pu238	feces	0.011261	0.029730	0.022523
5/12/02	5/12/2002	315	Pu239	feces	0.005405	0.029730	0.019369
	10/29/2001	120	Pu239	MS urine	0.000040	0.000300	0.000105
	11/24/2001	146	Pu239	MS urine	0.000080	0.000300	0.000082
	3/13/2002	**255**	**Pu239**	**MS urine**	**0.001025**	**0.000300**	**0.000173**
	5/10/2002	313	Pu239	MS urine	0.000012	0.000300	0.000028

Chest count on 11/14/01. No activity above background was detected.

Summary of PAS Results

- 143 filters in 94 days
- Cumulative exposure of
  - 39.2 DAC-hours with no PF applied
  - **23.0 DAC-hours with PF applied**
  - 10.6 DAC-hours with PF and DL applied

RPD-4   23.0 DAC-Hr (143 Filters in 94 Days)



RPD-5

Bioassay Results

Work Date	Date	Time (days)	Nuclide	Sample Type	Result (pCi)	DL (pCi)	2σ error (pCi)
7/5/01	7/9/2001	8	Am241	feces	0.014392	0.026405	0.020685
7/5/01	7/9/2001	8	Pu238	feces	0.005432	0.014459	0.010901
7/5/01	**7/9/2001**	**8**	**Pu239**	**feces**	**0.116757**	**0.017072**	**0.041491**
	11/8/2001	130	Am241	AS urine	0.004054	0.013063	0.008559
	11/8/2001	130	Pu238	AS urine	-0.001802	0.017117	0.003604
	11/8/2001	130	Pu239	AS urine	-0.007207	0.023423	0.007207
11/29/01	11/29/2001	151	Am241	feces	0.000000	0.025225	0.011712
11/29/01	11/29/2001	151	Pu238	feces	0.005856	0.017568	0.011712
11/29/01	11/29/2001	151	Pu239	feces	0.011712	0.017568	0.016667
2/19/02	2/21/2002	235	Am241	feces	0.014414	0.026126	0.020721
2/19/02	2/21/2002	235	Pu238	feces	0.000000	0.028829	0.015315
2/19/02	2/21/2002	235	Pu239	feces	0.010811	0.016216	0.015315
6/13/02	6/16/2002	350	Am241	feces	0.007207	0.009910	0.009009
6/13/02	6/16/2002	350	Pu238	feces	0.000000	0.005856	0.000000
6/13/02	6/16/2002	350	Pu239	feces	0.005856	0.005856	0.006757
	7/8/2001	**7**	**Pu239**	**MS urine**	**0.000779**	**0.000300**	**0.000668**
	11/29/2001	151	Pu239	MS urine	0.000131	0.000300	0.000035
	2/21/2002	235	Pu239	MS urine	0.000232	0.000300	0.001708
	6/14/2002	348	Pu239	MS urine	0.000104	0.000300	0.000038

Chest count on 11/8/01. No activity above background was detected.

Summary of PAS Results

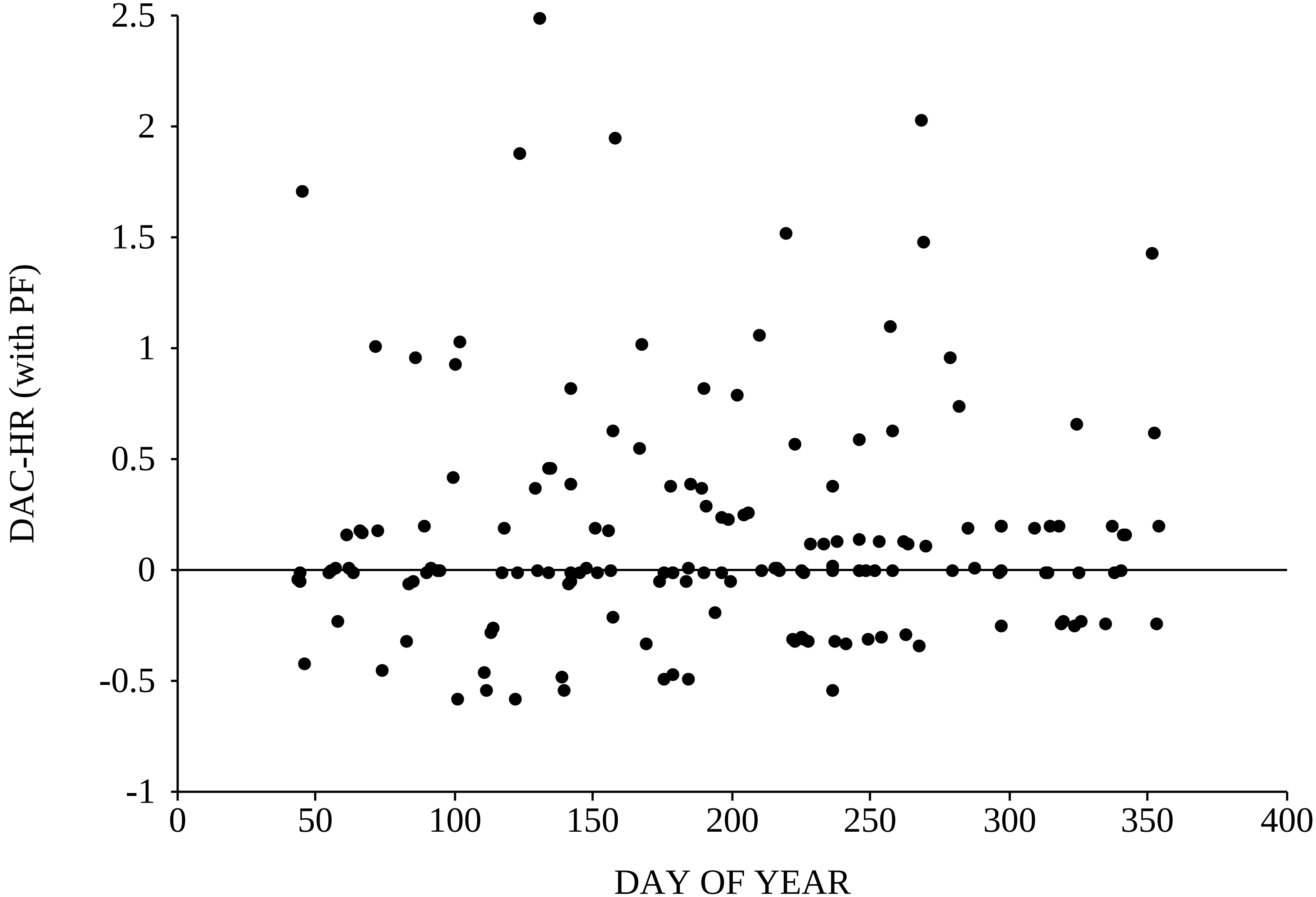
- 159 filters in 133 days
- Cumulative exposure of

  31.8 DAC-hours with no PF applied

  26.4 DAC-hours with PF applied

  19.8 DAC-hours with PF and DL applied

RPD-5 26.4 DAC-Hr (159 Filters in 133 Days)



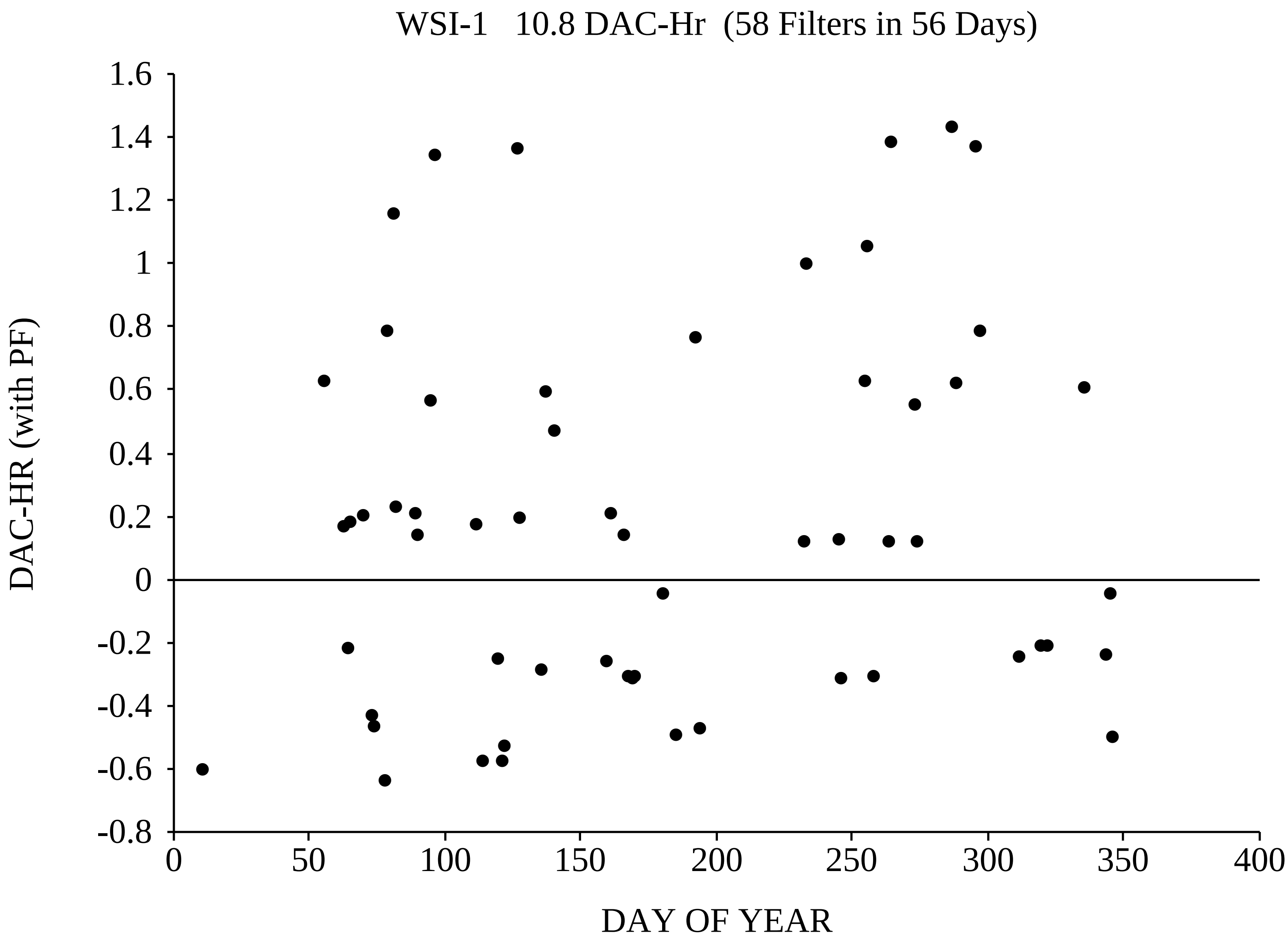
WSI-1

Bioassay Results

Work Date	Date	Time (days)	Nuclide	Sample Type	Result (pCi)	DL (pCi)	2σ error (pCi)
7/30/01	8/2/2001	32	Pu238	feces	0.004260	0.021806	0.012991
7/30/01	8/2/2001	32	Pu239	feces	0.000133	0.021806	0.009995
7/30/01	8/2/2001	32	Am241	feces	0.006770	0.020617	0.013383
	8/1/2001	31	Pu239	MS urine	-0.000047	0.000300	0.001012
	12/18/2001	170	Pu239	MS urine	0.000030	0.000300	0.000024
	3/2/2002	244	Pu239	MS urine	LIA		
	6/20/2002	354	Pu239	MS urine	0.000014	0.000300	0.000024

Summary of PAS Results

- 58 filters in 56 days
- Cumulative exposure of
  10.8 DAC-hours with no PF applied
  10.8 DAC-hours with PF applied
  9.1 DAC-hours with PF and DL applied


WSI-1 10.8 DAC-Hr (58 Filters in 56 Days)
DAC-HR (with PF)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
0
50
100
150
200
250
300
350
400
DAY OF YEAR

WSI-2

Bioassay Results

Work Date	Date	Time (days)	Nuclide	Sample Type	Result (pCi)	DL (pCi)	2σ error (pCi)
8/2/01	8/6/2001	36	Pu238	feces	0.002458	0.007369	0.004928
8/2/01	8/6/2001	36	Pu239	feces	0.004910	0.007369	0.006986
8/2/01	8/6/2001	36	Am241	feces	0.010784	0.016176	0.015333
	8/6/2001	36	Pu239	MS urine	-0.000005	0.000300	0.000049
	12/15/2001	167	Pu239	MS urine	-0.000099	0.000300	0.000158
	3/2/2002	244	Pu239	MS urine	-0.000038	0.000300	0.000154
	7/12/2002	376	Pu239	MS urine	0.000021	0.000300	0.000020

Summary of PAS Results

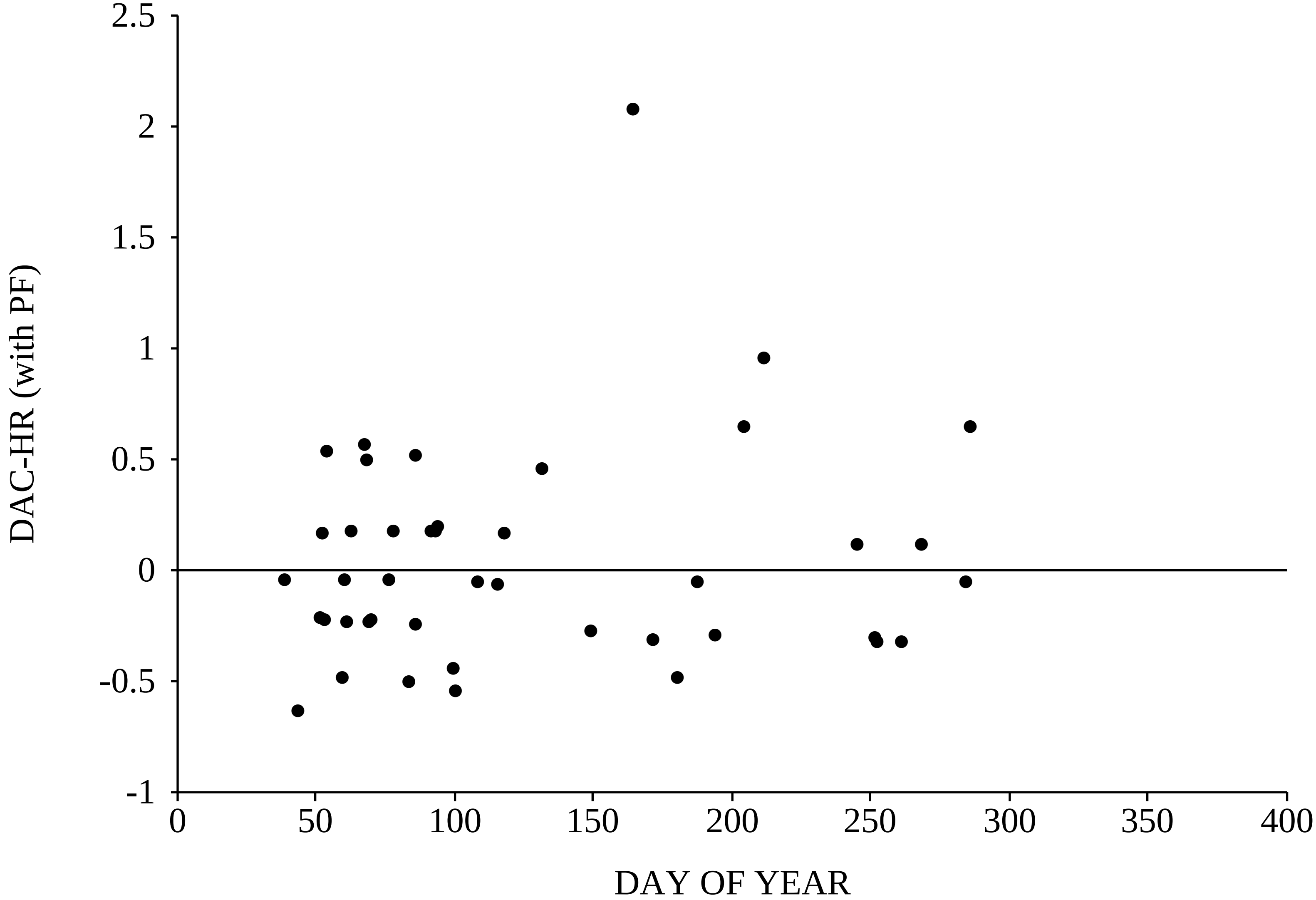
- 43 filters in 43 days
- Cumulative exposure of

    2.1 DAC-hours with no PF applied

    2.1 DAC-hours with PF applied

    2.1 DAC-hours with PF and DL applied

WSI-2   2.1 DAC-Hr (43 Filters in 43 Days)



WSI-3

Bioassay Results

Work Date	Date	Time (days)	Nuclide	Sample Type	Result (pCi)	DL (pCi)	2σ error (pCi)
8/8/01	8/13/2001	43	Pu238	feces	0.004057	0.012162	0.008149
8/8/01	8/13/2001	43	Pu239	feces	0.000000	0.012162	0.000000
8/8/01	8/13/2001	43	Am241	feces	0.007000	0.021320	0.013838
	8/11/2001	41	Pu239	MS urine	-0.000022	0.000300	0.000892
	12/20/2001	172	Pu239	MS urine	0.000062	0.000300	0.000048
	3/2/2002	244	Pu239	MS urine	0.000044	0.000300	0.000094
	5/28/2002	331	Pu239	MS urine	-0.000104	0.000300	0.000124

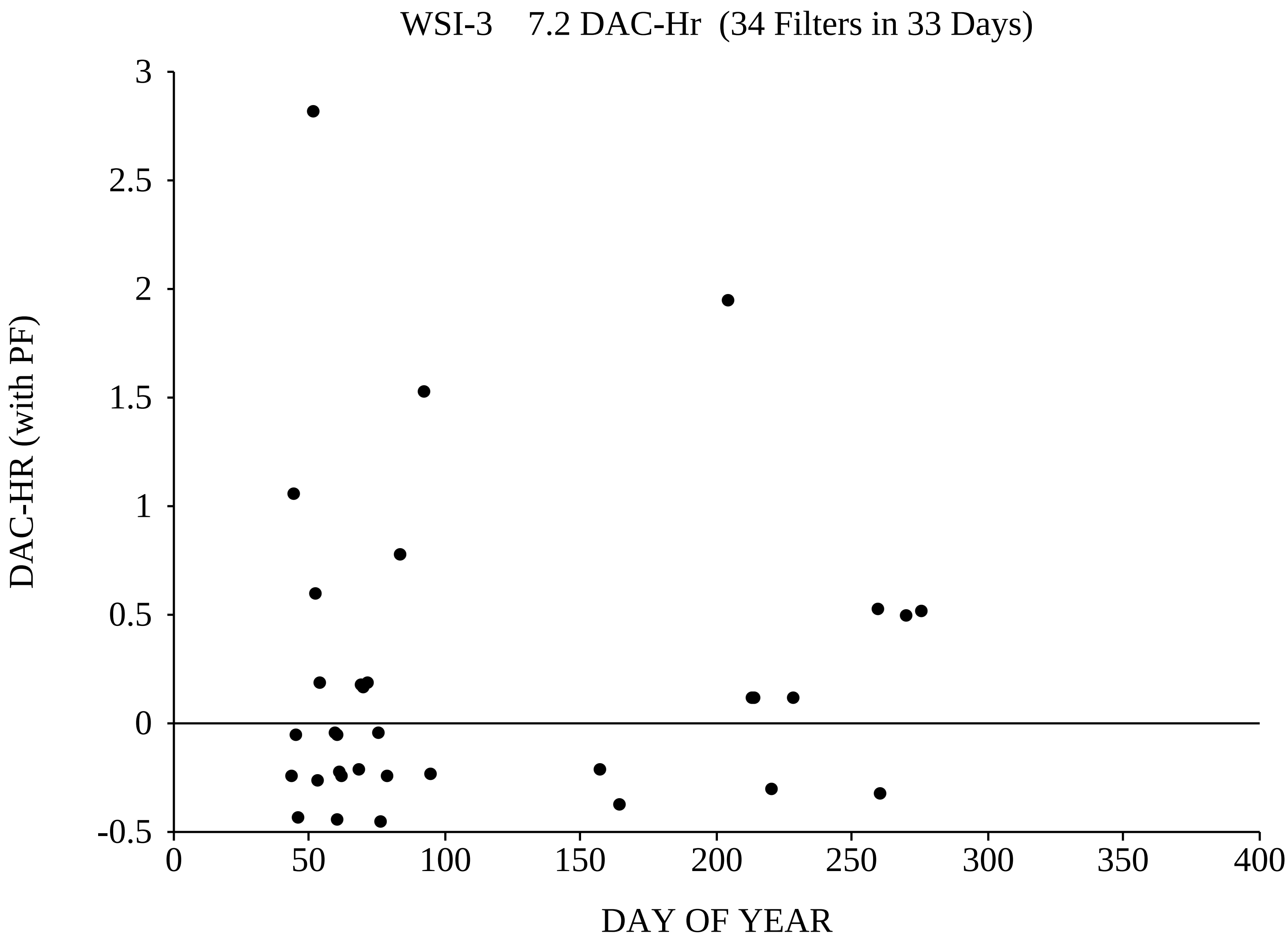
Summary of PAS Results

- 34 filters in 33 days
- Cumulative exposure of

  7.2 DAC-hours with no PF applied

  7.2 DAC-hours with PF applied

  7.4 DAC-hours with PF and DL applied


WSI-3 7.2 DAC-Hr (34 Filters in 33 Days)
DAC-HR (with PF)
3
2.5
2
1.5
1
0.5
0
-0.5
0
50
100
150
200
250
300
350
400
DAY OF YEAR

Appendix B.

The traditional rule-of-thumb states that 1 DAC-hour will deliver 2.5 mrem committed effective dose equivalent (CEDE). In this worksheet we show that there is a more accurate and equally useful conversion. Written in Mathcad 2001i. Relationships between SI units (which Mathcad knows) and traditional units (which it does not) are defined below. Note that Mathcad automatically converts to the desired units.

$$pCi := 0.037 \cdot Bq \qquad \mu Ci := 37000 \cdot Bq \qquad mrem := Sv \cdot 10^{-5} \qquad mL := \frac{liter}{1000}$$

The DAC for soluble Pu-239 given in 10CFR835 Appendix C is

$$DAC := 2 \cdot 10^{-12} \cdot \frac{\mu Ci}{mL}$$

This DAC, which is the most restrictive, is based on the non-stochastic dose limit of 50 rem to the bone surfaces instead of 5 rem to the whole body, i.e., it is a non-stochastic DAC. The non-stochastic DAC is used when air concentrations are reported in terms of DAC or exposures are reported in DAC-hours. Assuming a worker inhales 20 liters of air per minute (2400 m^3 per 2000 hour work year), a DAC-hour (which is actually the quantity of plutonium inhaled) is

$$DAChr := DAC \cdot (1 \cdot hr) \cdot \left(20 \cdot \frac{liter}{min}\right) \qquad DAChr = 2.4\,pCi$$

The traditional rule-of-thumb is that 1 DAC-hour will deliver 2.5 mrem, which is derived from the fact that 2000 DAC-hours equals an ALI, which will in turn deliver 5 rem CEDE. Using the intake-to-dose conversion factors (DCF) from Federal Guidance Report Number 11, we can calculate the dose from a 1 DAC-hour intake of soluble Pu-239.

non-stochastic	**stochastic**
$DCF_{ns} := 2.11 \cdot 10^{-3} \cdot \frac{Sv}{Bq}$	$DCF_s := 1.16 \cdot 10^{-4} \cdot \frac{Sv}{Bq}$
$DAChr \cdot DCF_{ns} = 18.7\,mrem$	$DAChr \cdot DCF_s = 1.0\,mrem$

Thus, an exposure of 1 DAC-hour reported by the air monitoring group will actually deliver 18.7 mrem to the bone surfaces and 1.0 mrem to the whole body in the 50 years following the intake. If the inhaled Pu-239 happened to be insoluble, the doses from a 1 DAC-hour intake would be

non-stochastic	**stochastic**
$DCF_{ns} := 8.21 \cdot 10^{-4} \cdot \frac{Sv}{Bq}$	$DCF_s := 8.33 \cdot 10^{-5} \cdot \frac{Sv}{Bq}$
$DAChr \cdot DCF_{ns} = 7.3\,mrem$	$DAChr \cdot DCF_s = 0.74\,mrem$

A more accurate and rather appealing rule-of-thumb emerges from these calculations, namely that 1 DAC-hour of plutonium (as reported by the air monitoring group) will deliver 1 mrem CEDE.